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Bicycle braking friction measurements on winter roads

Master's Thesis, Department of Civil and Environmental Engineering, School of Engineering, Aalto University

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Abstract of master's thesis

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Abstract

This master's thesis study has been carried out during a student exchange in the Norwegian University of science and technology in the Research Centre for Winter maintenance. The master's thesis consists of two parts: I) a process report and II) a manuscript for a scientific paper. In addition, appendix is marked as part III.

Bicycling is considered an attractive way of traveling since it improves health, is flexible and often fastest mode of travelling in urban areas. Therefore it is becoming more and more common mode of transportation in Scandinavia. Also several municipalities want their citizens to use bicycles. However, winter conditions set a challenge for providing a good and functional bicycle lane network. Winter maintenance actions, such as snow removal, gritting and salting, are needed. In order to assess the quality of these actions, they should be measurable.

The Norwegian Public Road Administration (NPRA) uses a standard for winter maintenance of bicycle lanes which include friction criterion for bicycle lanes. The standard defines that the friction value should be higher than 0,3. Friction measurement devices (FMDs) are used to control whether the conditions are within the specified standard. However, it is not known how well these values describe friction experienced by bicycles. The two objectives of this study are: 1) to measure actual braking friction of bicycles on winter conditions and 2) comparing the results to friction measurement devices (FMDs).

Two methods were used to measure bicycle friction in this study: deceleration and braking distance. Two instrumented bicycles with studded winter tires were tested by all-out braking tests on winter road surfaces. As a comparison, friction of the test stretch was measured by three FMDs. The results showed that both methods are suitable for defining bicycle friction, however, the deceleration is found to be a more accurate method in field conditions given. The bicycles experienced same or higher friction than the FMDs. The variability of bicycle friction was also higher than the variability of each individual FMD. This is probably due to lack of slip control of the bicycles and thereby it is uncertain whether all the attainable friction was used during the braking tests.

Keywords Friction, bicycle, bicycle lanes, winter conditions

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Tiivistelmä

Tämä diplomityö on kirjoitettu opiskelijavaihdossa Norjan teknis-luonnontieteellisessa yliopistossa talvikunnossapidon tutkimuskeskuksessa. Työ muodostuu kahdesta osasta: I) prosessiraportista ja II) tieteellisen artikkelin käsikirjoituksesta. Lisäksi liitteet ovat osassa III.

Pyöräily koetaan houkuttelevana liikkumismuotona, koska se on terveyttä edistävä, mukautuva ja tiiviissä kaupunkiympäristössä usein nopein tapa matkustaa. Sen vuoksi se lisää suosiotaan myös Pohjoismaissa. Myös useat kunnat haluavat nykyään asukkaidensa liikuvan matkansa enenevissä määrin pyöraillen, koska pyöräily ei huononna ilmanlaatua tai aiheuta ruuhkia. Sääolot heikentävät kuitenkin pyöräilyn houkuttelevuutta talvella ja oikeanlaiset talvikunnossapidon toimenpideet, kuten lumen ja jään poisto, hiekoitus ja suolaus ovatkin avainasemassa hyvien pyöräilyolojen saavuttamiseksi. Jotta näiden toimenpiteiden laatua voitaisiin arvioida, täytyy niitä pystyä mittaamaan.

Norjassa yhtenä hyvän talvikunnossapidon mittarina käytetään kitka-arvoa, jonka norjalaisten hoito-ohjeiden mukaan tulee olla suurempi kuin 0,3. Arvo mitataan standardin mukaisilla kitkamittareilla, jotka ovat tarkoitettu ajoratojen kitkan mittaamiseen ja ovat näin ollen soveltuvia kuvaamaan auton renkaan ja tien pinnan välistä kitkaa. Sitä ei kuitenkaan tiedetä, miten hyvin tällä tavoin mitattu kitka ja polkupyörän kokema kitka vastaavat toisiaan. Tämän työn tarkoituksena on 1) tutkia, miten polkupyörän jarrutuskitkaa voidaan mitata ja 2) verratta mitattuja tuloksia kitkamittareilla mitattuihin arvoihin.

Polkupyörän jarrutuskitkaa mitattiin kahdella menetelmällä: mittaamalla jarrutusmatkaa ja alkunopeutta sekä mittaamalla polkupyörän hidastuvuutta pyörään kiinnitetyllä kiihtyvyysanturilla. Tulokset osoittavat, että molempia menetelmiä voidaan käyttää polkupyörän jarrutuskitkan mittaamiseen. Kiihtyvyysanturilla mitattu kitka on kuitenkin paljon tarkempi kenttämittauksissa kuin jarrutusmatkan mittaamisella saavutetut kitka-arvot. Epätarkkuus jarrutusmatkamenetelmää käytettäessä aiheutuu jarrutuksen alkamispisteen epätarkkuudesta, sekä nopeusmittareiden epätarkkuudesta. Polkupyörillä tehtyjen mittausten välillä havaittiin suurempi hajonta kuin kitkamittareilla tehtyjen mittausten välillä. Tämä johtunee polkupyörien luiston ja jarrutusvoiman hallinnan puutteesta, mikä edelleen johtaa siihen, ettei jarrutustilanteissa välttämättä saavutettu maksimikitkaa. Polkupyörien kitka-arvot olivat kuitenkin vähintään yhtä korkeita, kuin kitkamittareilla mitatut kitka-arvot.

Avainsanat Kitka, polkupyörä, pyörätiet, talviolot

Preface

This master's thesis is written for the Department of Civil and Environmental Engineering at the School of Engineering at the Aalto University, Finland. Field test and writing process itself has been carried out in Norwegian University of science and technology (NTNU). Depart from ordinary master's thesis, this thesis consists of two parts: a process report and a manuscript for a scientific paper. The decision to write the thesis in this form is based on a request by my thesis advisor Alex Klein-Paste at the NTNU, which was confirmed by my supervisor Terhi Pellinen at the Aalto University.

The process report describes the actual process for the study, which results are presented in the scientific paper. In this way the required quality and the level of details for a master's thesis is achieved. In other words, this process report presents the parts of the study that didn't fit in the paper and also extends the content to match with the requirements of a master's thesis. The process report describes also the roles of the university supervisors and advisors whereas the scientific paper presents the method and results of the study.

It has been an instructive, challenging and in the end, rewarding process to write the thesis in this form. The thesis has also been presented during the study process in *Teknologidagene* in October 2014 in Trondheim, Norway and in *Transportforum 2015* in Linköping, Sweden in January 2015. In addition the results have been presented in several meetings in the Norwegian public roads administration during the spring 2015. The writing process together with holding presentations in conferences and meeting has been a new and exciting experience for me. I sincerely thank my thesis advisor Alex Klein-Paste for all the support, encouragements, interesting discussions and seamless cooperation during this study. I also thank my supervisor Terhi Pellinen for supporting and making it possible to write my thesis abroad on this topic in this form.

In addition I want to sincerely thank Jarkko Valtonen, Teaching Researcher, D. Sc. (Tech.), Department of Civil and Environmental Engineering at the Aalto University for the important support and example that he was during my studies at the Aalto University. I also want to thank my former co-workers at the Highway laboratory in Aalto University for the inspiring atmosphere and the good moments together.

Trondheim, 8th April 2015

Katja-Pauliina Rekilä

Content

Abbreviations

NPRA	Norwegian public roads administration
VTI	Swedish National Road and Transport Research Institute
FMD	friction measurement devices
μ	friction coefficient
F_μ	friction force
F_n	normal force
a	acceleration
g	gravity
l	braking distance
E_k	kinetic energy
F_b	braking force
v	initial speed of a bicycle
$a_{b/n}^{n}$	acceleration in bicycle's coordinate system
$a_{b/n}^{b}$	acceleration recorded by accelerometers
$R_b^n(\Theta_{nb})$	rotation matrix

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Process report

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1 Introduction

1.1 Background

Bicycling is getting more and more popular mode of transport all over the world. One reason for this is the increasing amount of traffic which leads to more congestion, especially in the urban areas. Therefore transport modes, which are faster and easier to use and produce less congestion and air pollution, like bicycling, are getting more attractive. In addition, bicycling is a physical activity which can increase health. Due to these advantages, several cities and municipalities also want more people to use bicycle and preferably whole year around. However, winter conditions in the Nordic countries set a challenge to year around bicycling and the number of bicyclists in winter time is significantly lower than in summer time. Providing functioning bicycle network also in winter requires winter maintenance actions, such as snow and ice removal, sanding and salting. The quality of these actions needs to be accessed in order to know whether the actions are effective. In Norway, one indicator for this is friction. Friction is measured with devices that are developed to measure friction on car lanes and are therefore describing how a car experiences friction. However it is not known how well these devices are describing the friction experienced by bicycles.

In Norway, there are 650 friction measurement devices in total in use on roads in every winter season. The friction measurement devices (FMDs) are used to monitor the winter maintenance quality on the road network. In order to get comparative values, all the FMDs approved by the Norwegian directorate of public roads are calibrated towards five reference FMD which further are calibrated towards one standard FMD in the beginning of each winter season. In this study, three FMDs were used: a TWO™, a passenger car and a T2GO™. Of these three the TWO™ and the passenger car with a deceleration instrument are standardized devices approved by the Norwegian public roads administration and are representing the Norwegian standard for friction measurements on roads. The TWO™ consist of a two standardized measuring wheels without studs. The wheels are installed sequentially back of a van having a weight equivalent to 75 kg. The commonly used measuring speed is 60 km/h. One of the wheels is rolling freely and one has a constant slip value, usually 20 % is used. This means that the measuring wheel is rolling 80 % of the speed of the freely rolling tire and the vehicle. The portable T2GO™ is also approved by Norwegian public roads administration but it isn't calibrated towards the standard. The T2GO™ is operating in different speed than the standard devices and therefore it is found to be challenging to calibrate it. The standard devices operate approx. in speed of 60 km/h whereas the T2GO™ operates in walking speed.

The offset to this master's thesis was a study made in Sweden, where friction of bicycle lanes was measured with a special friction measurement device developed by the Swedish National Road and Transport Research Institute (VTI) (Bergström, Åström and Magnusson, 2003). However, the study didn't take a stand on how well the measurements correspond with the friction that bicycles experience. In order to evaluate whether different friction measurement devices can be used on bicycle lanes, the comparison of experienced bicycle friction needs to be measured and compared to friction values measured by different friction measurement devices. For this purpose, friction experienced by bicycles needs to be measured, but no method for this exists. In general, studies related to bicycle friction on winter conditions seems to be lacking in the open literature.

1.2 Purpose

This study has two purposes: 1) to develop a method to measure bicycle friction on winter conditions and 2) to compare the bicycle friction to the friction measurement devices. In order to achieve this, field studies were carried out to measure bicycle braking friction with two different methods. To understand how bicycle friction is corresponding to friction values measured by friction measuring devices, the values has been compared with the friction values measured by different devices.

1.3 Limitations

This study concentrates only on bicycle braking friction and not on steering friction. In addition, only the winter conditions were tested that were available during the field test day. Two friction measurement methods, braking distance and deceleration, were the most convenient ones to measure and were therefore chosen for this study. Other possible methods, like torque and friction force measurements, were excluded from this study since they require a fully instrumented bicycle that wasn’t available for this study.

2 Methodology

This study consists of three parts: 1) literature study, 2) field work and 3) data analyzing.

2.1 Literature study

The research process started with a literature study of mapping what is already known about bicycle friction or winter maintenance of bicycle lanes. Mainly science direct, Google Scholar, search engine for Norwegian universities and colleges (BIBSYS Ask) and Aalto University library's search engines were used to find scientific articles, books reports from reliable authors. Since the topic is relevant mainly in cold regions, soon the search results were also centered on this region. Literature in other languages than English, Norwegian, Finnish and Swedish were excluded.

It was found hard to find research papers of friction measurements on bicycle lanes or papers of bicycle friction. Also literature related to winter maintenance of bicycle lanes except for standards were lacking. It seemed that most of the standards for bicycle lanes are based on existing standards for car lanes and usually parallel bike lanes and the car lanes get same standard. Most of the literature found related to the bicycle performance and friction was simulation studies. Also more literature was found related to summer bicycling than winter bicycling. The simulation studies were not suitable, since in this study the focus was to find out the correlation between experienced friction and measured friction, so actual field tests were required. In simulation studies, friction is usually an input factor to the simulation program and doesn't necessary have much to do with real experience, especially in winter conditions. The literature found in the literature study is described in the chapter 1 in the part II.

2.2 Field work

For the data collection purpose, a field test day was carried out in April 2014 in Dovre, Norway. It was challenging to find a suitable area for the field test purpose, since there hadn't been much snow during the winter season and it was already end of the season. Together with the Norwegian public roads administration, a suitable spot was found eventually in a mountain area at Dovre municipality in a stopping place along European route 6 (E6). The weather conditions stayed more or less constant through the test day. It was sunny winter weather with very little wind and no precipitation. Though, the sun radiation together with the braking measurements loosened the test surface during the day. This gave two different weather conditions during the test day: hard compacted snow on morning and large grained compacted snow on afternoon. This was found to be an advantage, since it enabled to compare two different surface conditions.

The Norwegian public roads administration was included in the field test day by providing the comparative friction measurement devices. Originally four different friction measurement devices were planned to use: TWO™ by Pon-Equipment AS, which is a continuous friction measurement device installed behind a van; an optical RCM411 sensor by Teconer, a passenger car with an instrument to record the deceleration by

Coralba Roads and a portable friction measurement device T2GO™ by ASFT Industries AB (Table I-1).

Table I-1 Reference friction measurement devices

TWO™ by Pon-Equipment AS	Included
Teconer RCM411	Included
Passenger car with Coralba µ™ deceleration measurement device	Excluded
T2GO™ by ASFT Industries AB	Included

However, the optical sensor needed to be excluded from the study because it measures mean friction value over a longer distance and the test stretch for this study was too short to be measured with it. Therefore the TWO™, passenger car and T2GO™ were included as reference friction measurement devices for this purpose (Figure I-1). These devices were chosen since they were the ones that were available for the field test.

Figure I-1. The reference friction measurement devices used in the study. From left: TWO™, T2GO™ and passenger car with Coralbra µ™.

In order to have larger variety in the results, two different bicycles were chosen to be tested: a hybrid bicycle and an off-road bicycle. The hybrid bicycle had three seasons used studded winter tires and the off-road bicycle had unused studded winter tires (Part II: Figures 1 and 2). The hybrid tires were narrower than the off-road tires. By choosing different bicycles with different tires enabled to have a larger representative of the existing bicycles in the bicycle traffic. Studded winter tires were chosen because in Norway almost every year-round bicyclist prefers studded winter tires. The hybrid bicycle was instrumented by the thesis advisor before the test day. This covers the tire speed pulse counter and accelerometer. The tire speed pulse counter was installed in both tires, but before the real test execution, it was found out that the data logger wasn't recording data from one of the tire speed counters. Therefore the thesis advisor suggested that both brakes should be used equally in the braking tests. The master candidate instrumented the off-road bicycle at the field test site together with the thesis advisor. The summary of the used equipment is given in Table I-2 below.

Table I-2 The test bicycles' equipment

Bicycle	Bicycle number	Tire type	Speed measurement device	Deceleration masurement device
Hybrid	1	Studded, hybrid, narrow	Pulse counter	3-axis accelerometer
Off-road	2	Studded, terrain, wide	GPS	3-axis accelerometer

The braking distance was measured with a simple measuring tape. Each braking started with bicycling up till 25 km/h and then braking hard with both brakes after a marker. The brakings were chosen to be repeated ten times in the morning with each bicycle and five times in the afternoon. During the afternoon measurements, the surface conditions were changing and therefore less braking tests were repeated in order to preserve the delicate surface conditions. The tests were chosen to be repeated on the same spot. First the whole series of brakings were carried out with the hybrid bicycle and then with the off-road bicycle. This same order was repeated both in the morning and afternoon. In this way it was possible to have a short time difference between the brakings with one bicycle, since the same bicyclist could do the brakings continuously without changing the bicycle in between. This also enabled to collect a one continuous data set over all the sequential braking tests for each bicycle. In this way it was easier to read and analyze the data afterwards.

2.3 Data analyzing

The master candidate started the data analyzing process with calculating the bicycle braking friction measured by braking distance in order to see whether reasonable values were collected. The handling of the braking distance data didn't include more than reading values from the raw data files. The collected data was initial speed data both from pulse counter for bicycle 1 and from GPS data for bicycle 2. Each value was collected according to the time when each braking took place. Since the data collecting devices were more accurate than the time wrote time manually for each braking, several initial speed values were available. For this study, the master candidate chose the highest value of these values for each braking test and used that as an initial speed value. The braking distance data was written in a note paper at the test site and were copied to a MS Excel file as an initial speed data afterwards. Thereby a simply calculations for the friction value form braking distance data could be calculated in Excel according to the equation 3 in the chapter 1 in the part II. For comparison, the friction values measured by FMDs were also copied to the MS Excel file and the collected field data looked promising already at this point.

For the accelerometer data analyzing purpose, a numerical computing program MATLAB® R2014a by MathWorks was used by the master candidate. The MATLAB® was suggested to be used by the thesis advisor since the amount of accelerometer data form the field was enormous and for an efficient data analyzing purposes a proper tool is needed. The biggest advantages in the MATLAB® is that after programming, it allows the user to repeat the same mathematical actions to a large amount of data in short time. However, the master candidate didn't have any previous experience of the program, or programming whatsoever in deeper level, so the candidate needed to learn both. The thesis supervisor helped the candidate to get started with the program by writing a simple script for importing the raw data from accelerometers to the program, filtering the data for plotting purposes and plotting it before the test day. This script was used in the field to collect data from accelerometer and to be saved into a computer.

The data had a lot of noise and needed to be filtered in order to interpret it. A common method for filtering a digital signal data is to use a running average filter, which was also used in this study. The filter was chosen by the thesis advisor. The filter calculates an average within a certain number of data on either side of the central value. The number of data points included in calculating this average is called window size and for this study it was 256, which was half of the sample rate of the accelerometers. This window was shifted over the entire data set value by value creating and returning a new data set of averaged numbers. In this way the data got a readable form. Together with the filtering the date and time of the data set was also fixed to match with the time marker done in the field before the tests. The time marker was done simply by tilting the bicycles which was seen as a high peak in the y-axis in the accelerometer data. This peak was fixed to match with the time marker's time and further the whole time data column could be corrected.

The filtering and time correction made it possible to interpret the data. Each test run was seen as a clear peak in the x-axis. The moment when the bicycles were held straight and still, the resultant of all the three axes was 1g, meaning that at this moment the x and y axes should be 0g and z-axes 1g. However, the master candidate soon discovered that before getting any usable results out of the data, the accelerometers' coordinate systems needed to be rotated to match with the bicycles coordinate system and that rotating a 3-axes coordinate system was more complicated than rotating a 2-axes coordinate system. The master candidate used a basic trigonometry to calculate the angles, θ, Φ and ψ, between the coordinate systems of an accelerometer and a bicycle at that moment when the bicycle was standing still for each bicycle. The values for g-forces recorded by the accelerometer at this moment were used to describe a length of a vector. The master candidate calculated the angles between a vector that was vertical and had the length of 1g. The candidate used these angles to calculate the rotation matrix for right handed coordinate system. The rotation matrix is from Euler's rotation theorem, where a coordinate system is rotated around each three axis as follows: roll (θ) around x-axis, pitch (Φ) around y-axis and yaw (ψ) around z-axis, as commonly used to describe a position of an airplane. An illustration of this rotation between the two coordinate systems is presented in the part II, in chapter 2.2. Each measurement with 3 g-values for each axis was handled as a vector and each of these vectors were then multiplied with the rotation matrix. The new vector was then describing the g-forces of each axis of the bicycle at that specific moment. The Euler's angle transformation is given in equation 5 and the rotation matrix in equation 6 in the part II.

After the Euler's rotation, the master candidate saw that the axes weren't at 0g when the acceleration was 0g in real life and therefore the data needed to be fine-tuned. It wasn't sure whether the bicycles really were standing straight at the moment where the angles were calculated and this might cause the error in the data. The fine-tuning was done by checking whether the acceleration before each braking was 0g. At these points the bicycle was moving straight with constant speed, in other words, at these points the acceleration should be 0g. This fine-tuning was done by multiplying the data with a factor that shifted the whole data to 0g at those moments. Eventually, the results were possible to read from the data and compared to the braking distance data. Since the friction coefficient factor calculated form braking distance data was a mean value for each braking, the mean acceleration value needed to be calculated from the accelerometer data also. This the candidate did by simply calculating mean acceleration between data points where each braking starts and ends.

The master candidate decided to do a statistical comparison between braking distance data and accelerometer data to see whether there is a difference between the results. This was done by chosen to use Student's T-test for comparing the mean friction coefficient values from the braking tests. The null hypothesis whether the mean of the two samples were equal was tested. The test was chosen by the master candidate. The results were also plotted against each in other to see how well the data correlates suggested by the thesis advisor. The correlation is presented in the part II in figure 7. The deviation between the two methods is presented in a histogram in figure 8 also in the part II. The comparison showed that there is no difference between the methods. Next, the error for both methods was calculated by estimating the accuracy of each measured factor. The idea for error estimation came from the thesis advisor. The error estimation for both data is presented in the part II in chapter 4.1. The error inspection showed that the accelerometer data is more accurate method for measuring bicycle braking friction than the braking distance data.

At last all the accelerometer data, that was shown to be more accurate, was chosen to be compared against data from other friction measurement devices. The mean friction value for each measurement measured by each FMD was calculated and plotted in the same figure as a function of time. This figure is presented in the part II in figure 9. The low number of data points didn't allow a statistical comparison to be done between the different FMDs and bicycles. Each group of measurement didn't have that big of a scatter but the figure shows a large variation between bicycles and different measurement devices and therefore the results were chosen to be presented in this way by the master candidate.

3 Results

For this study, in total 30 braking test, 15 with each bike, were done. These braking tests are called runs. The results are presented in the part II in chapter 3 in Table 1. All the raw data is presented in the part III in an appendix in the end of this thesis. Each braking test is in chronological order starting from the run 1 and ending in run 30 including all data from each run.

4 Progress description

The research idea for this thesis came from the thesis advisor. The Norwegian Public Roads Administration (NPRA) started a four years research and development program for winter maintenance in the beginning of 2013. The program aims to contribute to better accessibility, regularity, reliability and availability in winter time for all road users. The program has been divided in four subprojects: 1) salting and chemicals, 2) friction and road surface conditions, 2) ITS (intelligent transport systems) and decision support and 4) method development. Part of the program is being carried out through cooperation with the Norwegian University of Science and Technology (NTNU), especially in the field of salting and friction and road surface conditions. Therefore a research center for winter maintenance (*Forskningsenter vinterdrift*) at the NTNU has been established in cooperation with NPRA. The thesis advisor Alex Klein-Paste is also the head of the research center and suggested this topic after the master candidate had shown high motivation towards combination of winter maintenance and everyday traveling in urban areas.

4.1 Study plan

The master candidate formulated a study plan in the summer 2014, when it was clear that this project will be the master's thesis for the candidate. At this point, the field studies had been carried out already and therefore the study plan needed to be based on them. The research questions for this study at that point was: how bicycles experience friction and can the existing friction measurement devices be used to measure quality of winter maintenance actions on bicycle lanes. This was found out to be a topical issue at the moment, since a new standard for winter maintenance on bicycle roads was published in the beginning of year 2014 with a friction coefficient limit value 0,3. Same time more and more focus has been put on attractiveness of year-round-bicycling.

The starting point for this study was a doctoral study by Anna Bergström from the Royal Institute of Technology, Stockholm, Sweden (2002), where she was measuring friction of bicycle lanes with a portable friction measurement device. In her study, she didn't compare the device to real friction experience but suggested that such comparison should be carried out. However, after a literature study, the master candidate found out that a method for bicycle friction measuring didn't exist and therefore a new research question was formed: how bicycle braking friction can be measured.

During the study process, the master candidate had discussions with the thesis advisor, first every second week and later each week regularly. In each meeting, the goal to next meeting was set. This kept the study going forward effectively. To these discussions the candidate usually came with questions related either to the structure of the thesis and writing process itself, or interpreting the results. The thesis advisor usually didn't give straight answers but tested the candidate and helped the candidate to see the problem in wider perspective and therefore to solve the problems herself. These dialogues played the key role in the whole process, since they really taught the candidate the most. It was during these discussions when the candidate had the biggest epiphanies and got inspired.

4.2 Field work planning and execution

Doe to the short notice, the field test day was arranged by the thesis advisor. At this point it wasn't sure yet whether the study will end up being a part of a master's thesis for the candidate and therefore the thesis advisor was leading the field work planning and execution. However, the master candidate contributed the planning by having an active dialogue with the thesis advisor before, during and after the field work. The amount of braking tests and a question whether the tests should be repeated on same spot or not, was decided by the master candidate after a discussion with the thesis advisor.

Bicycle braking test with the bicycles were carried out by the master candidate. Timekeeping and bookkeeping during the bicycle braking tests were taken care by the thesis advisor. Test stretch markings, braking distance measurements and comparative friction measurements with FMDs was carried out by Norwegian public roads administration. Additional measurements, such as temperature, tire pressure and tire shore hardness, were carried out by the thesis advisor, since he knew how to use the measuring instruments, whereas the master candidate was a bookkeeper. More accurate weather information was got by the candidate afterwards from the Norwegian Meteorological Institute (MET Norway). All the field test day data was saved and taken care by the master candidate.

4.3 Data analysis and conclusions

The further work started with learning the use of MATLAB®, analyzing the data, carrying out the literature survey and eventually writing the thesis. The choice of the program was suggested by the thesis advisor. Carrying out the programming and data analyzing with the MATLAB® was made by the master candidate. The master candidate also found out the Euler's angle rotation method for correcting the positions of the accelerometers. In addition, the candidate decided also to carry out a statistical analysis for the results and chose the method for that. The conclusions were made by the master candidate and discussed together with the thesis advisor. The discussions helped the candidate to conclude only the most relevant outcomes of this study.

4.4 Learnings

The learning outcomes of this study are many. In a bigger perspective the master candidate learned how to conduct a research and how to carry out a field work. The candidate didn't have opportunity to plan the field work, but during the data analyzing part, the candidate learned what relevant information to collect from the field next time. The candidate has already used these learnings later in life, while carrying out a new field work study independently. The writing process in this scale has also been a new experience and especially expressing oneself in English was an instructive process. It has also been a new experience for the candidate to write a scientific paper. The more practical learning outcomes have been learning to use MATLAB® that the candidate finds an extremely useful skill also later in life. During the process the candidate learned a lot about friction and tribology. A whole new world of friction opened and now the candidate is eager to continue working with the subject further on. One of the most rewarding learning outcomes has been the ability to see how important it is to make critical judgements. The whole study process taught to the candidate was to see which questions the collected data actually answers and what cannot be concluded of the given data.

5 Concluding remarks and further work

The study shows that bicycle friction can be measured. In order to make further conclusions about how well different friction measurement devises are capable of describing friction that bicycles experience, more studies needs to be done. It seems that a large number of factors are affecting the friction value that are not evaluated in this study. It is not known how these different factor affect to the friction coefficient value, but it’s expected that doe to these factors, different friction mechanisms are attending in different friction measurement situations. This study didn’t focus on which friction mechanisms are attending when braking with a bicycle or when measuring friction with a FMD. More studies are required in order to get a full understanding of the interaction between a bicycle tire and a winter road surface. These studies should be extended to studying the friction mechanisms needed while steering a bicycle, not just braking it. The most dangerous situations with bicycles happens when steering the bicycle and then suddenly losing side friction. Usually in these situations the bicyclist cannot do much for preventing to fall. For understanding the friction mechanisms in these situations it is possible to provide safer and better bicycle lanes in winter time by executing right kind of winter maintenance actions. This can further result in year-round bicycling to become more attractive and popular.

Part II

Manuscript for a scientific paper

Katja-Pauliina Rekilä, Alex Klein-Paste

MEASURING BICYCLE BRAKING FRICTION IN WINTER CONDITIONS

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Abstract

Bicycling is considered an attractive way of traveling and it is becoming more and more common mode of transportation in Scandinavia. However, winter conditions set a challenge for providing a good and functional bicycle lane network. Winter maintenance actions, such as snow removal, gritting and salting, are needed. The Norwegian Public Road Administration (NPRA) uses a standard for winter maintenance of bicycle lanes, which include friction criterion for bicycle lanes. Friction measurement devices (FMDs) are used to control if the conditions are within the specified standard. However, it is not known how well these values describe friction experienced by bicycles. The two objectives of this study are: 1) to measure actual braking friction of bicycles on winter conditions and 2) comparing the results to friction measurement devices (FMDs). Two methods were used to measure bicycle friction in this study: deceleration and braking

NPRA	Norwegian public roads administration
VTI	Swedish National Road and Transport Research Institute
FMD	friction measurement devices
$a^n_{b/n}$	acceleration in bicycle's coordinate system
$a^b_{b/n}$	acceleration recorded by accelerometers
$R^n_b(\Theta_{nb})$	rotation matrix

distance. Two instrumented bicycles with studded winter tires were tested by all-out braking tests on winter road surfaces. As a comparison, friction of the test stretch was measured by three FMDs. The results showed that both methods are suitable for defining bicycle friction, however, the deceleration is found to be a more accurate method in field conditions given. The bicycles experienced same or higher friction than the FMDs. The variability of bicycle friction was also higher than the variability of each individual FMD. This is probably due to lack of slip control of the bicycles and thereby it is uncertain whether all the attainable friction was used during the braking tests.

Research highlights: In situ bicycle braking tests were carried out. Bicycle braking friction was measured with two methods. A perceived bicycle braking friction was compared to friction measurement devices.

Keywords: Bicycles; friction; measurements; winter; maintenance

1 Introduction

1.1 Background

Bicycling is considered an attractive way of traveling since it is healthy, flexible and, especially in urban areas, can be faster than other modes of transportation. Several studies have shown a positive correlation between physical activity and increase of health (Wang et al., 2004 and Tesche et al., 2012). In addition, walking and cycling can decrease congestions and improve the environment. Accordingly, the Norwegian National Transport Plan state that the growth in local travel in largest urban areas must be absorbed by public transport, cycling and walking (Norwegian directorate of public roads, 2012). To be more precise, the goal is to increase the account of bike trips from 4 % in 2009 to 8 % in 2023 (Espeland and Amundsen, 2012). To achieve this goal, better and safer infrastructure for pedestrians and bicyclists must be provided.

In the cold regions of the world, winter conditions create a challenge for maintaining good quality biking infrastructure. In Sweden, the number of bicycle trips in wintertime amounts to only one-third of the bicycle trips in summer time (Bergström, 2003). In the bicycle manual by Norwegian Public Roads Administration (NPRA) it is defined that the maintenance level of sidewalks and bicycle lanes should be as good as the standard for the adjacent road (Norwegian Public Roads Administration, 2014a). During wintertime, this demands the use of winter maintenance actions such as salting, snow removal and gritting. These actions are often performed by private contractors. The Norwegian standard for winter maintenance, describes a minimum friction coefficient value for the bicycle lane (Norwegian Public Roads Administration, 2014b). This value is measured by NPRA using standard friction measurement devices. However, little is known on how standard friction measurement devices correlate with friction experienced by bicycles. In Sweden, a study has been carried out to measure the friction coefficient value of a bicycle lane with a portable friction tester developed by the Swedish National Road and Transport Research Institute (VTI). The results showed that the tester is suitable for measuring the friction of the bicycle lanes. Nevertheless, the study did not show how well this friction tester describes the performance of bicycles (Bergström, Åström and Magnusson, 2003). Attempts to measure bicycle braking friction on winter conditions appear to be lacking in the open literature. The two objectives of this study are therefore: 1) to measure actual braking friction of bicycles on winter conditions and 2) to compare the results to friction measurement devices (FMDs).

1.2 Measuring bicycle friction in winter conditions

Friction measurements have mainly focused on heavier vehicles such as motorbikes, cars, and airplanes (Klein-Paste et al., 2012; Andresen and Wambold, 1999). Slippery and slip-resistant footwear performance has also been studied (Aschan et al, 2009). Computer-based modelling and simulation has developed substantially over the last two decades, which is resulting in that bicycle dynamics related studies are mainly carried out virtually. The computer-based modeling and simulation is usually inexpensive and time-saving and therefore more attractive to use than experimental field tests. Nevertheless, more accurate results are achieved by experimental testing (Day, 2014). The simulation studies for bicycles are focused either on bicycle rider control and motions (Moore et al., 2010; Schwab and Meijaard, 2013) or on braking vibration and analysis (Redfield, 2014; Lie and Sung, 2010). Apart from Bergström, Åström and Magnusson (2003), very few studies are done on friction measurements on bicycle lanes covered with snow or ice.

Friction is a force between two materials sliding against each other. Friction is always dependent not only the properties of the two materials but also the ambient environment and the interfacial medium between the materials. This complex interaction is called tribosystem. Generally, friction is expressed by the friction coefficient value, μ, which is a ratio between friction force, F_μ, and normal force, F_n (Equation 1).

$$\mu = \frac{F_\mu}{F_n} \qquad \textbf{Equation 1}$$

Friction is needed to control a bicycle since it enables steering, braking and accelerating. In general, friction of a vehicle can be measured in four different ways: measuring friction force, deceleration, torque or braking distance (Hall et al., 2009; Andresen and Wambold, 1999; Day, 2014). In this study, deceleration and braking distance are used, since they are most convenient to measure. In addition, measuring friction force or torque requires a fully instrumented bicycle, which was not available for this study. The relationship between deceleration, *a*, and friction coefficient, μ_a, can be defined from the equation 1 and it is:

$$\mu_a = \frac{a}{g} \qquad \textbf{Equation 2}$$

where g is gravity (Lie and Sung, 2010). On a flat road, friction can thus be determined by measuring the deceleration of a fully braking vehicle. The braking distance, *l*, is dependent on initial speed, *v*, and mass, *m*, of a bicycle.

The friction can also be measured by measuring the braking length of a vehicle that came to a complete stop as shown in Equation 3. This requires also measurements of the initial speed. Further, friction is dependent on initial speed and the braking distance as follows:

$$\mu_{\boldsymbol{b}} = \frac{\boldsymbol{v^2}}{\boldsymbol{2lg}} \qquad \textbf{Equation 3}$$

While measuring bicycle friction, it is important to attain maximum available friction from the road surface. For the case of bicycles this might be a challenge since bicycles do not have ABS systems.

2 Method

2.1 Test execution

For this study, friction of two ordinary bicycles was measured on winter road conditions in April 2014. This was executed by all-out braking experiments. The bicycles were sped up to approximately 25 km/h and braked hard as hard as safely possible until thee bicycle came to a full stop. The mean friction coefficient was measured both by deceleration of each braking (Equation 2) and by braking distance together with initial speed of a bicycle (Equation 3). The braking tests were done in series: one series with each bike in the morning and one series with each bike in the afternoon. Friction coefficient values were also measured by friction measurement devices (FMDs) on the test stretch before and after the braking test series as a comparison. There were three FMDs: TWO™ by Pon-Equipment AS, which is a continuous friction measurement device installed behind a van; T2GO™ by ASFT Industries AB, a portable continuous friction measurement device; and a passenger car with a deceleration detector by Coralba. The TWO and the passenger car with the deceleration detector were calibrated towards a standard friction-measuring device used in Norway earlier the winter.

In Norway, it is common that bicyclists use studded winter tires in bicycles during winter season. Therefore test bicycles with studded winter tires were chosen to this test. Two types of winter tires were used: bicycle 1 had 3 seasons old used winter tires (hybrid tires), and bicycle 2 had unused winter tires (terrain tires) (Figure 1 and 2). Both bicycles were equipped with 3-axis accelerometers with right hand coordinate system, 512 Hz sample rate, accuracy of ±2 g and resolution of 15 bit. Additionally, bicycle 1 was equipped with a tire speed pulse counter with 18 magnets and a data logger and bicycle 2 had a GPS to record the initial speed. All instruments used on the bicycles were synchronized with the GPS clock.

Figure 1: The tire of the hybrid bicycle (bicycle 1).

Figure 2: The tire of the terrain bicycle (bicycle 2).

The test site (Figure 3) was located in the municipality of Dovre in Norway on a parking lot along highway E6, halfway between Dombås and Hjerkinn. During the test day, the weather was sunny with no precipitation, wind speed 2 m/s, air temperature -1,4 °C and mean relative humidity 61,5 %. Road surface temperature was -9 °C, measured in the middle of the test day between measurement series. Two different winter road surface conditions were tested. During the morning tests, the surface of the test stretch was hard compacted snow. During the afternoon tests, the surface was softened by the sun and it started to disintegrate into loose, large grained snow grains on top of an ice-based layer (Figure 4 and 5).

Figure 3: The test stretch starting at the red marker with a length meter on a side.

Figure 4: Road surface conditions in the morning.

Figure 5: Road surface conditions in the afternoon.

The measurements were done in following order. First, the friction coefficient value of the test stretch was measured by two friction measurement devices: TWO™ and T2GO™. Then, ten braking tests were done with bicycle 1 and then with bicycle 2, respectively. Last, the friction coefficient value was measured again instantly after the braking tests with the TWO™ and the T2GO™. At this point, snow and air temperatures were measured. In the afternoon, the same procedure was repeated. However, only five braking tests were done with each bicycle instead of ten in order to preserve the delicate surface conditions of the test stretch as much as possible. Eventually the passenger car was used to measure friction coefficient value of the test site three times. The passenger car was only used after the testing in order to avoid destroying the test stretch. Bicycle 1 had 2,9 bar in back tire and 3,4 bar in front tire. The mean shore hardness was measured to be 61,4 in back and 60,0 in front. Bicycle 2 had 2,0 bar in both tires with a mean tire shore hardness of 54,0 in back and 60,0 in front.

2.2 Processing the data

The friction value by braking distance was calculated from the measured braking distance and initial speed data. A maximum speed just before braking was read manually from both initial speed data. Then the mean friction coefficient values for each braking were calculated according to Equation 3.

Determination of μ_a required processing of the raw data. The accelerometer data contained noise that needed to be filtered, which was done by using a running average through the data with a window size of 256.

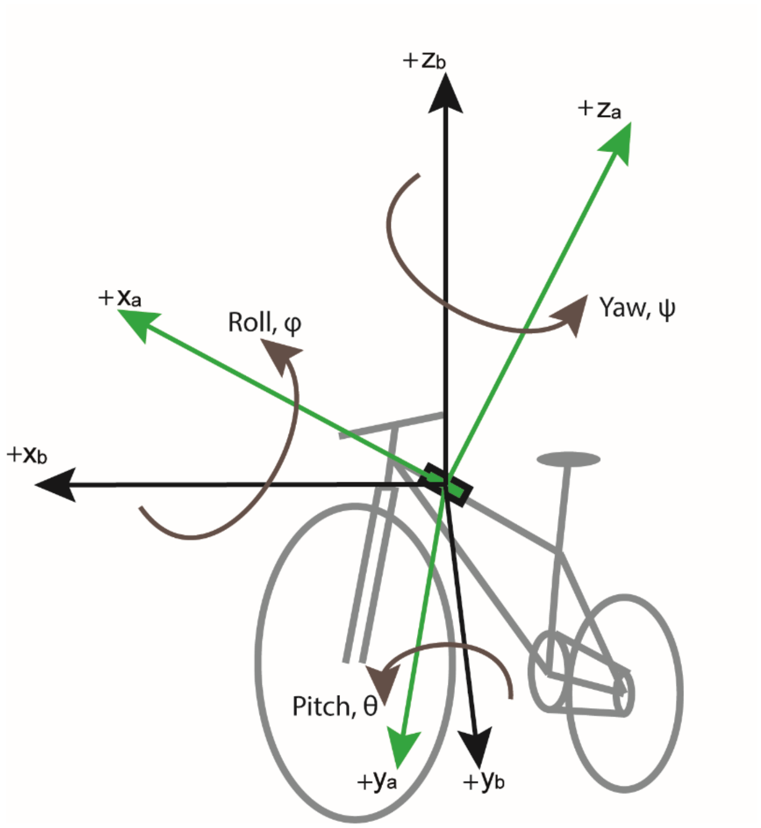


Figure 6: An illustration of the rotation between bicycle's (b) coordinate system (black) and accelerometer's (a) coordinate system (green).

The coordinate system of the accelerometers had to be aligned with the bicycles' coordinate system, illustrated in figure 6. This was done by using Euler's angle transformation (Fossen, 2011) given in Equation 5.

$$\boldsymbol{a_{b/n}^{n}} = \boldsymbol{R_{b}^{n}(\Theta_{nb})a_{b/n}^{b}} \qquad \textbf{Equation 5}$$

where the $a_{b/n}^{n}$ is the real acceleration in bicycle's coordinate system and $a_{b/n}^{b}$ is the acceleration recorded by the accelerometers. The rotation matrix $R_{b}^{n}(\Theta_{nb})$ is given in the Equation 6.

$$R_{b}^{n}(\Theta_{nb}) = \begin{bmatrix} \cos(\psi)\cos(\theta) & -\sin(\psi)\cos(\phi) + \cos(\psi)\sin(\theta)\sin(\phi) & \sin(\psi)\sin(\phi) + \cos(\psi)\cos(\phi)\sin(\theta) \\ \sin(\psi)\cos(\theta) & \cos(\psi)\cos(\phi) + \sin(\phi)\sin(\theta)\sin(\psi) & -\cos(\psi)\sin(\phi) + \sin(\theta)\sin(\psi)\cos(\phi) \\ -\sin(\theta) & \cos(\theta)\sin(\phi) & \cos(\theta)\cos(\phi) \end{bmatrix} \qquad \textbf{Equation 6}$$

where φ is roll, θ is pitch and ψ is yaw, which are the Euler's angles (Figure 6).

Each Euler's angle was derived from the accelerometer data. First, the angles were derived by gathering mean acceleration values of each of the three axes when the bicycles were held straight and still before the tests. Each mean acceleration value was used as a value to describe a length of a vector, x_a, y_a and z_a in Figure 6, and thereby by using basic trigonometry the angles could be derived. Then, the Euler's angle transformation was used to calculate accelerations of each bicycle according to Equations 5 and 6. At last, the data was fine-tuned in a way that vectors $x_a = x_b = 0g$ and $y_a = y_b = 0g$ and vector $z_a = z_b = -1g$ while the bicycle had a constant speed before each braking. Each raw dataset given by each accelerometer was processed separately to get as accurate results as possible.

An example of a processed dataset (and Euler's angle transformation and the fine-tuning) is presented in the Figure 7. The ten braking tests can be seen as distinct negative peaks on the x-axis (red).

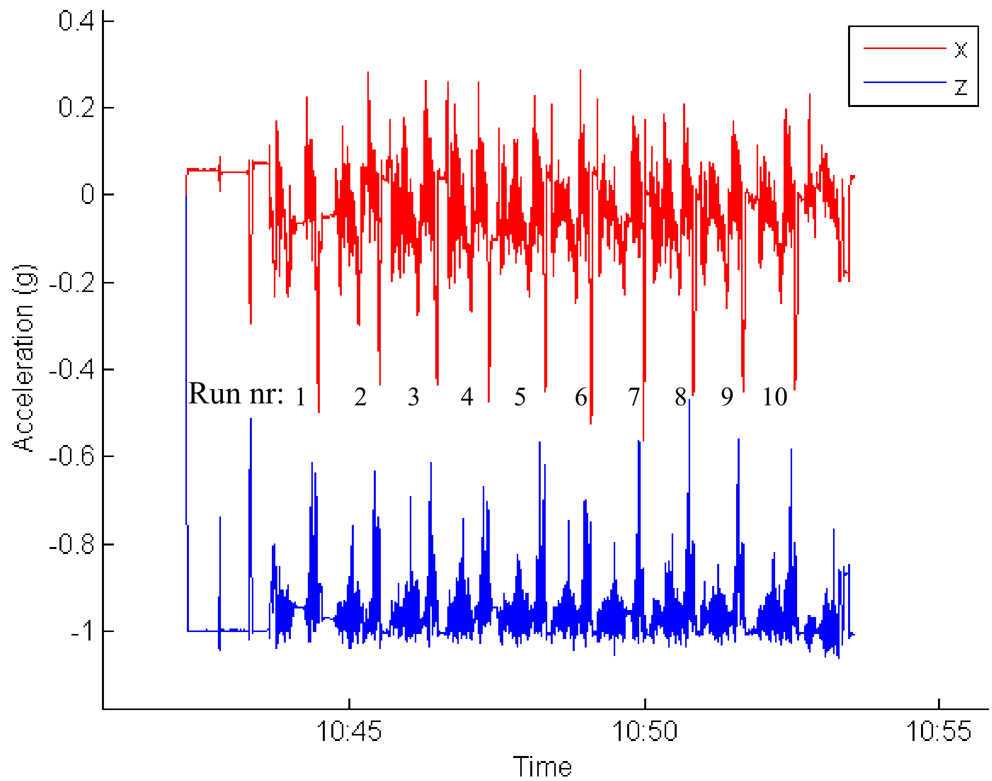
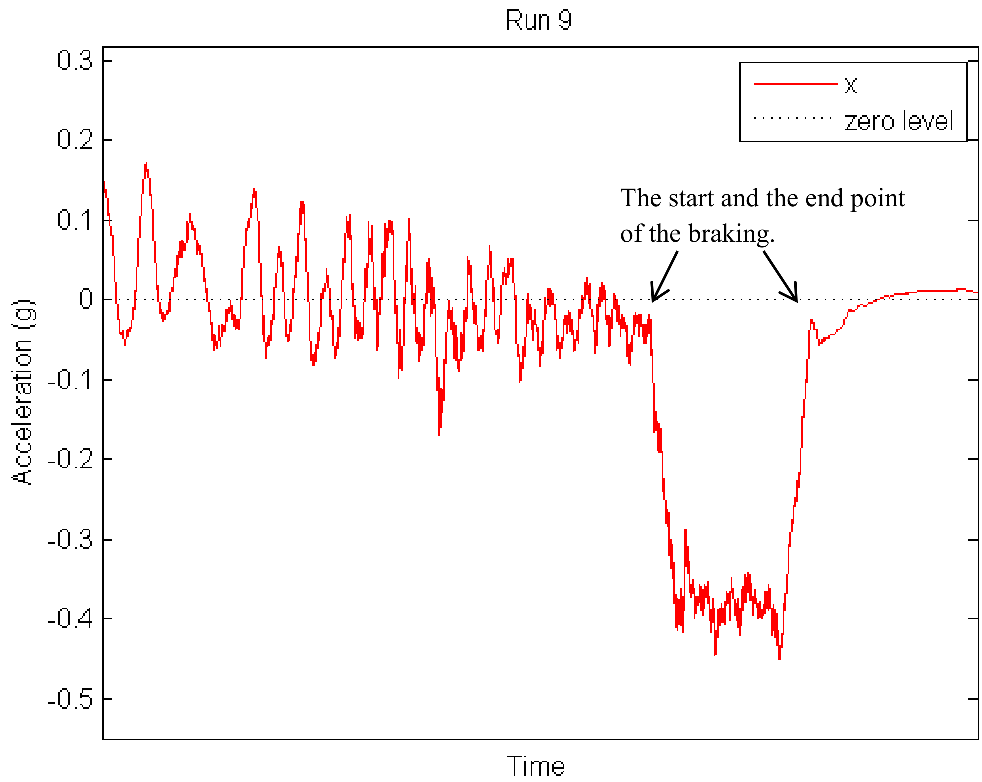


Figure 7: Example of a filtered and processed data from an accelerometer

The mean friction coefficient value of each braking was obtained by calculating the mean acceleration of each individual deceleration peak sensed by the x-axis of the accelerometer. This was done by defining the area manually from a graph for each braking. An example of a graph (run no. 9, bicycle 1) is presented in Figure 6, where the g-force is around 0 when the bike is moving with a constant speed forward and then dropping down when the bicycle is braking. After the braking, the bicycle is standing still and the acceleration is 0g. The variation of the g-force during the constant speed results from the unevenness of the road surface. The mean friction values are defined from the area that has start- and end-points marked with arrows (Figure 8).



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224 **Figure 8: Accelerometer data for run no 9 with bicycle 1.**

3 Results

3.1 Bicycle friction measurements

In total 30 braking tests were performed, 15 tests with each bicycle. The results are presented in the Table 1. Due to technical problems, the initial speed data was not available in the afternoon.

Table 1 Friction values of the bicycles 1 and 2 on two different road surface conditions.

	Bike	v initial	v initial	Braking distance, l	µb	µa	Absolute error
Run nr	1 or 2	km/h	m/s	m	braking dist.	accelerometer	|Δµa-µb|
1	1	27	7,50	8,3	0,35	0,35	0,00
2	1	25,5	7,08	8,8	0,29	0,31	0,02
3	1	25,5	7,08	8,0	0,32	0,32	0,00
4	1	26	7,22	7,4	0,36	0,34	0,02
5	1	26	7,22	7,9	0,34	0,34	0,00
6	1	26	7,22	7,6	0,35	0,36	0,01
7	1	27	7,50	7,4	0,39	0,41	0,02
8	1	25,5	7,08	7,0	0,37	0,34	0,03
9	1	26	7,22	7,9	0,34	0,34	0,00
10	1	26	7,22	7,9	0,34	0,32	0,02
11	2	25	6,94	5,8	0,42	0,46	0,04
12	2	24	6,67	5,2	0,44	0,43	0,00
13	2	25	6,94	5,7	0,43	0,43	0,00
14	2	24	6,67	5,4	0,42	0,39	0,02
15	2	25	6,94	6,1	0,40	0,40	0,00
16	2	25	6,94	6,3	0,39	0,42	0,03
17	2	25	6,94	6,1	0,40	0,43	0,03
18	2	25	6,94	6,0	0,41	0,36	0,05
19	2	23	6,39	6,7	0,31	0,42	0,11
20	2	24	6,67	5,9	0,38	0,37	0,01
21	1	-	-	5,1	-	0,36	-
22	1	-	-	5,2	-	0,44	-
23	1	-	-	5,1	-	0,39	-
24	1	-	-	5,1	-	0,44	-
25	1	-	-	5,6	-	0,45	-
26	2	-	-	4,2	-	0,41	-
27	2	-	-	4,6	-	0,44	-
28	2	-	-	4,3	-	0,45	-
29	2	-	-	4,0	-	0,40	-
30	2	-	-	5,1	-	0,41	-

Comparison between the two methods is presented in Figure 9, where the friction from braking distance is plotted against the friction from acceleration is. In the same figure, a line of perfect correlation is shown as dash line and an outlier is marked as a red filled square. The Figure 9 shows that the scatter of the data is centred on the line of perfect correlation. A two-tailed paired t-test was used to test whether the two methods give the same results. The p-values are 0,86 for bicycle 1 and 0,46 for the bicycle 2. Hence, there is no statistically significant difference between the methods.

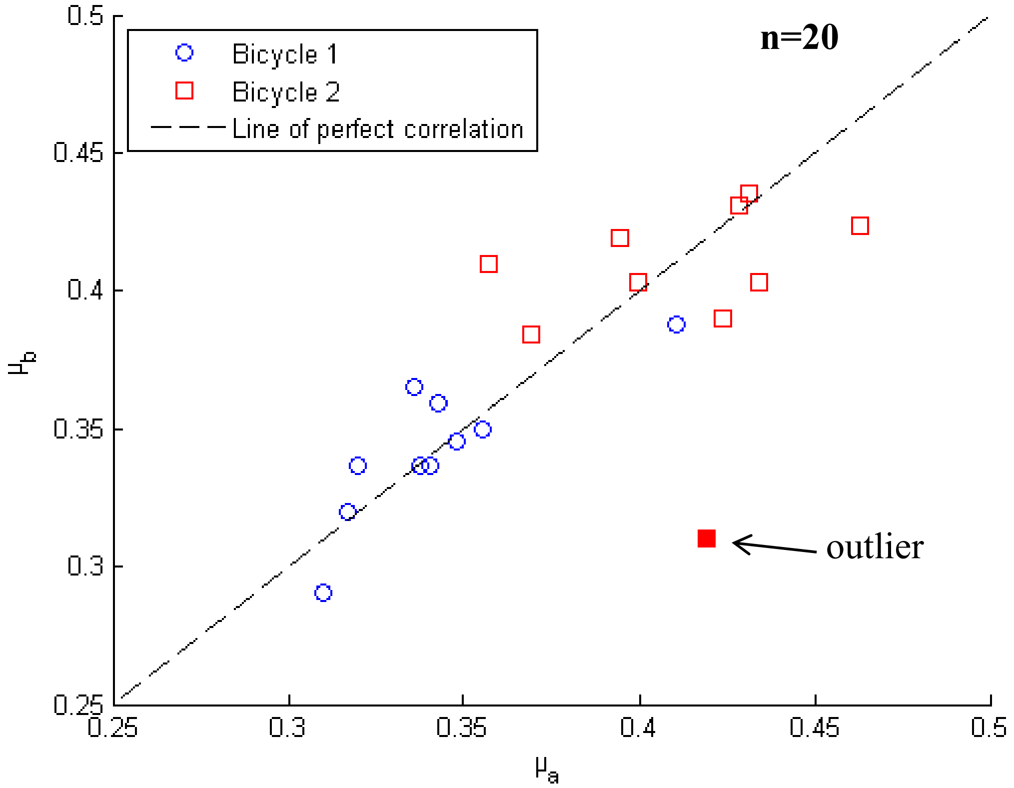

Figure 9: The correlation between friction values from accelerometer (x-axis) and braking distance (y-axis) for bicycles 1 and 2. The outlier is marked as filled square.

The deviation between the two methods is presented in the Figure 10. The deviation is symmetrical around zero and appears to have a normal deviation.

The absolute difference between the two methods is also presented in the Table 1 on the right column.

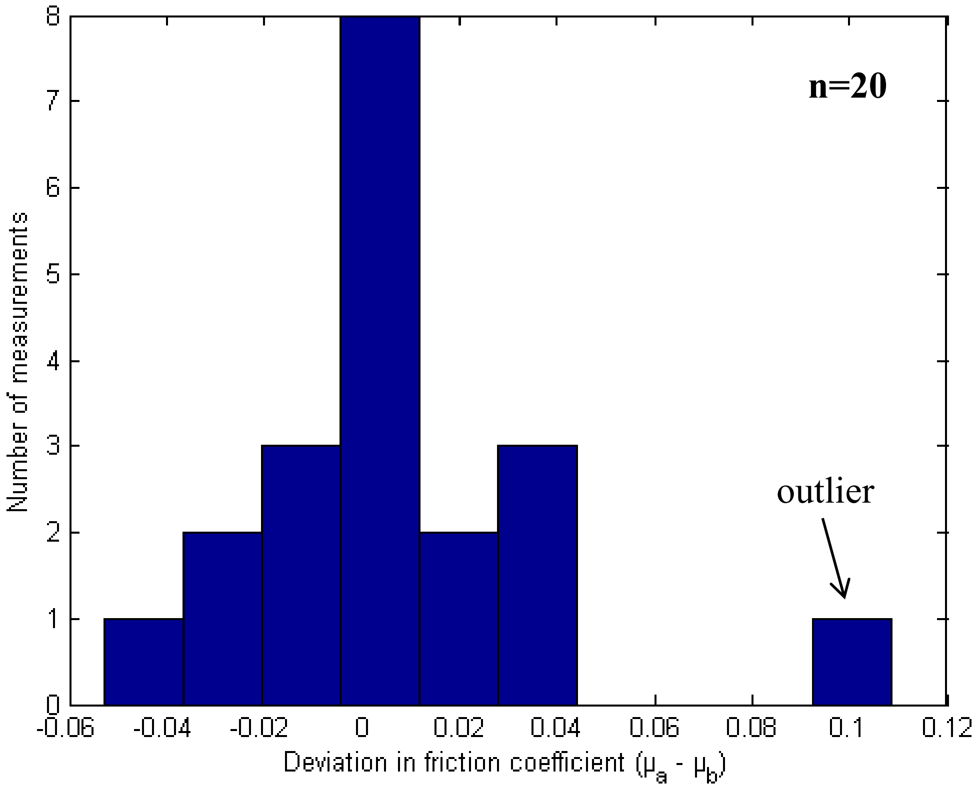

Figure 10: The deviation between the two methods for each braking test.

3.2 Comparison of friction values between bicycles and friction measurement devices

A comparison of the friction values measured by accelerometer data and different FMDs is presented in the Figure 11. The results show that the bicycles experienced equally or more friction, compared to the FMDs. The scatter in the bicycle data is larger than the scatter in each FMD. However, the different FMDs varied significantly from each other. The portable T2GO™ measured consistently lower values. The passenger car has the next lowest values. TWO™ had the highest values from all FMDs but still lower values than the bicycle 1 and bicycle 2.

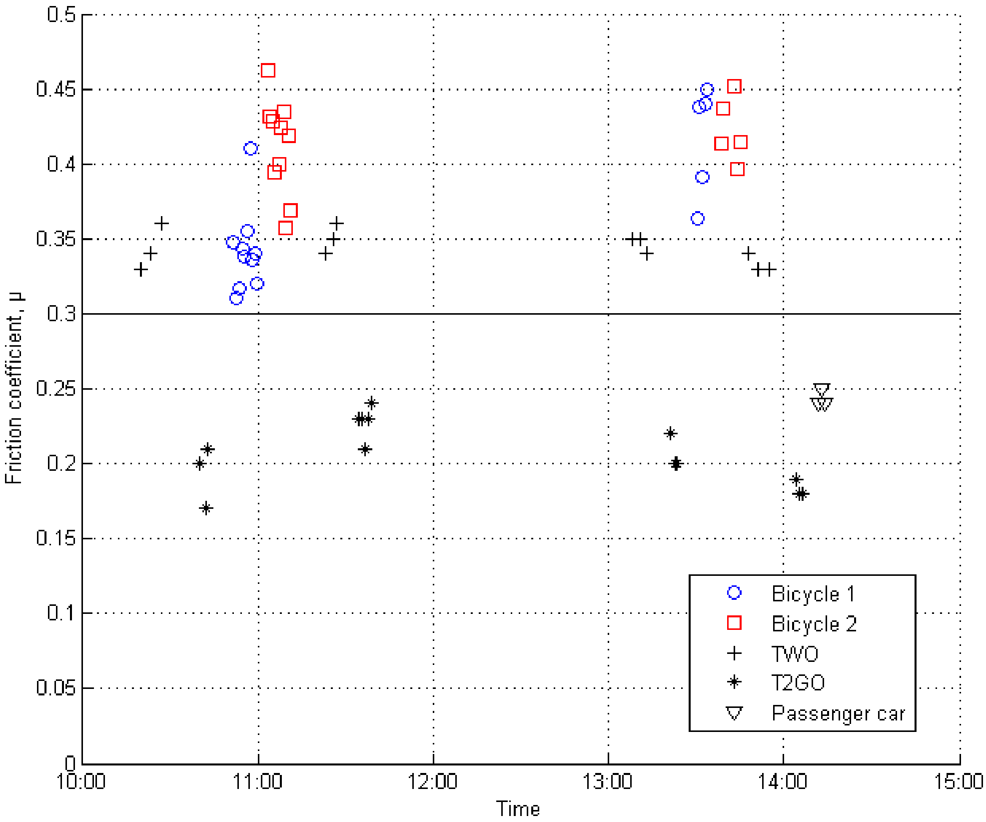

Figure 11: Friction coefficient values from all measurements with the minimum friction level from standard.

4 Discussion

4.1 Quality assessment of bicycle friction measurement methods

The results show a good correlation between the two friction-measuring methods, deceleration and braking distance (Figure 7). Therefore, in principal, both methods can be used to measure a bicycle friction coefficient. The deviation (Figure 8) shows that there is no systematic error between the two methods, which indicates a confirmation that the fine-tuning of the accelerometer data has been successful.

Good quality friction-coefficient-calculations by the braking distance method require accurate braking distance measures as well as accurate initial speed measurements. In this study, it was experienced to be difficult to start braking exactly at the marker starting point. In field experiments, the variation in the starting point of each braking can introduce inaccuracy into the friction values. In this study, the error in the braking length was estimated to be ±0,4 meters. Another important factor that affects the accuracy in the friction value is the initial speed since it is raised to a second power in Equation 3. A standard GPS does not necessary give accurate enough speed values for a bicycle, since the speed can vary at short notice. A better method for detecting the initial speed is to use a high resolution tire speed pulse counter, preferably for both tires. The error for the initial speed, Δv, was estimated to be ±2 km/h for this study. A simple error propagation into the friction coefficient is explored in Table 2. The Table 2 shows that an error up to ±0,10 can be explained by the inaccuracies of braking distance and initial speed measurements. The one outlier in the data (Figures 7 and 8) most likely resulted from starting to brake too late.

Table 2 Calculations for estimating the impact of the error to the mean friction coefficient value, μ.

	v (km/h)	l (m)	μb	Error to mean μb
Estimated error $\pm\Delta$	2	0,4		
Mean values from data:	25,3	6,2	0,41	
v, $l-\Delta l$	25,3	5,8	0,43	0,03
v, $l+\Delta l$	25,3	6,6	0,38	−0,02
v+Δv, l	27,3	6,2	0,47	0,07
v−Δv, l	23,3	6,2	0,34	−0,06
v+Δv, $l+\Delta l$	27,3	5,8	0,51	**0,10**
v−Δv, $l-\Delta l$	23,3	6,6	0,32	−0,08

The errors in the acceleration measurements are mainly related to the calibration and alignment of the sensors and to tilting during a braking event. The calibration of 3-axis accelerometers can conveniently be performed when the sensor is at rest, because the resultant acceleration is exactly 1g. It is expected that this is not causing error in the friction values. The error due to alignment was minimized through the fine-tuning and it is therefore expected to result not more than ±0,25° incorrect alignment of the sensor. The error $\Delta\mu_x$ due to tilting in given in Equation 7. A ±0,25° misalignment results in an error $\Delta\mu_x$ = ±0,004 in friction value (Equation 7). In addition, the accelerometer data can contain inaccuracy resulting from the bike tilting during the hard braking. The tilting causes a component of the gravitational force (z-axis of an accelerometer) to be included to the friction force. For this study, the bicycles were estimated to tilt ±2° at the most, because of unlocked front suspensions. The calculated error ($\Delta\mu_x$) in friction values due to the tilting is calculated to be ±0,035 according to Equation 7.

$$\Delta\mu_x = \pm\sin\alpha \qquad \textbf{Equation 7}$$

where α is the angle between coordinate systems of the bicycle and the sensor. In order to avoid tilting, it is recommended to lock the front suspension. It could be useful to use an accelerometer combined with a gyroscope to compensate for the tilting factor. For the angle transformation, it is preferred to hold the bicycle still while standing straight for a period so that the vectors of the accelerometer and the angles relative to the bicycle can be defined. It is necessary to use a level that ensure that the bicycle is standing straight and the surface is flat while doing this. The inaccuracy to friction coefficient values resulting from the precision of the used accelerometers is ±0,001. The total error in the accelerometer data is thereby estimated to be $\Delta\mu_x$ = ±0,040.

The error calculations for these two test methods show that the accelerometer data is more reliable than the braking distance data given that the accelerometer is well aligned to the bicycle.

4.2 Comparison of friction of the bicycles and the FMDs

During the measurements, the bicycles experienced at least as much or more friction from the road surface, compared to the readings of from the different FMDs. There may be different reasons for this observation: First, the bicycles were equipped with studded winter tires, contrary to the FMDs. Second, the bicycles had higher tire pressure than the FMDs. Third, the slip speed, though it was not measured, is probably lower for the bicycles than for the TWO™ and the passenger car. Since the measurements are only performed on a limited number of surface conditions it is too early to draw firm conclusions if the bicycles usually experience more friction or that this is a case-specific result. However, if bicycles indeed structurally experience higher friction, one might wish to develop a correlation to adjust friction measurement devices used for bicycle lanes. Such correlation should ensure a whole range of surface conditions.

The variability of bicycle friction was higher compared to the variability of each individual FMD. This is not surprising, since bicycles differ significantly from the other FMDs in a way that the bicycles create a very simple braking system. The bicycles have no ABS system or no control over the slip rate whereas the FMDs have a fixed slip of 20 %. In addition, manual brakes are used. Therefore, it is uncertain whether all the attainable friction was used during the braking tests. Multiple braking tests are therefore advised to obtain an average friction value.

4.3 Use of friction standard on bicycle lanes

During this study, the more general question “should we have a friction criterion at all in the standard for bicycle lanes?” was often posed. Some colleagues and bicyclists pointed out that when biking with studded winter tires, slippery conditions are not a real problem. They seem to prefer a hard and even surface instead of a certain friction. Indeed in presence of loose snow on top of bicycle lanes appeared to be hampering winter cycling more than simply a “slippery surface”. However, bicycle lanes are not always used by bicyclist with studded winter tires alone. Nor it is possible to prevent other road users, such as a mother with a pram, a wheelchair user or an elderly person with a walker, to use the bicycles lanes as well. By removing the friction criterion, there would not be real criterion to initiate antiskid treatment such as gritting. Some sort of friction criterion seems therefore sensible, but as the data in Figure 9 illustrates, there is a large variation between different FMD’s and bicycles. A better definition on what is an acceptable friction criterion on bicycle lanes is therefore desirable.

5 Conclusions

The bicycle braking friction was measured with two different methods, deceleration and braking distance on winter road surface conditions. Both methods were found to be suitable for measuring bicycle friction and they are convenient and inexpensive to use. The inaccuracies to the braking distance method were mainly caused by two factors: 1) the accuracy of the determining the starting point of the braking and 2) the initial speed measurement. The deceleration data is found to be more accurate in field conditions, given that the accelerometer is properly aligned with a bicycle. The bicycle braking friction measurements exhibited more variation compared to each friction measurement device. This is probably caused due to a lack of slip control during braking. It is difficult to ensure that all attainable friction is indeed utilized during the braking. During the investigated conditions (compacted snow and loose snow grains on ice) the bicycles experienced at least as much friction as measured by the FMD's. The question whether it is sensible to use friction criteria to describe a winter standard on bicycle lanes is discussed.

6 Acknowledgements

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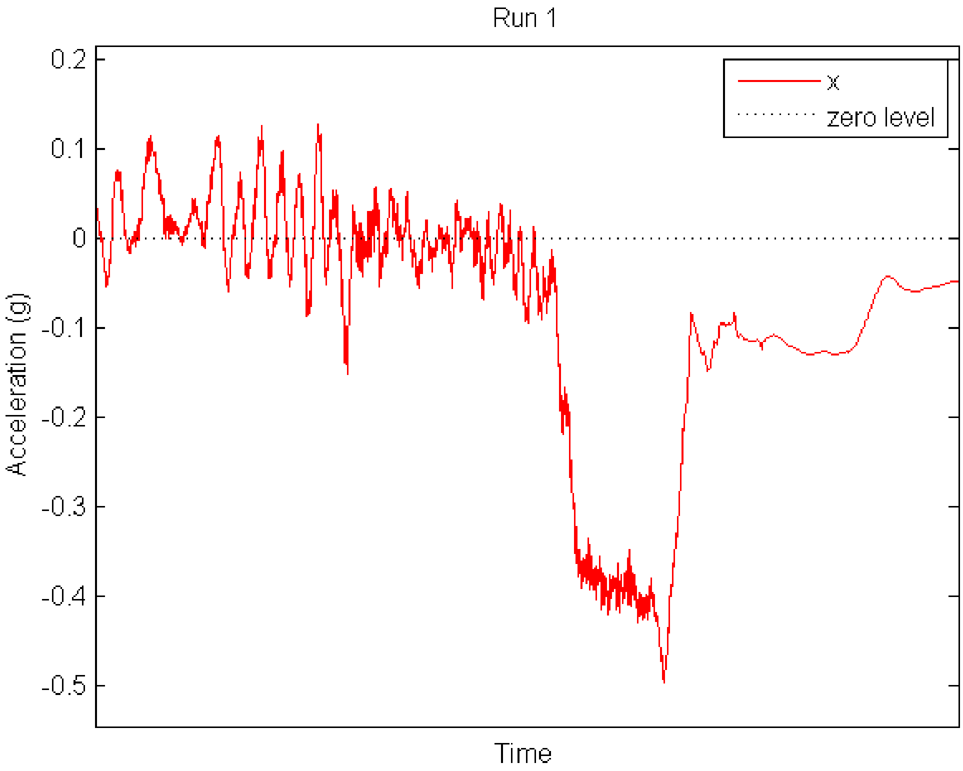
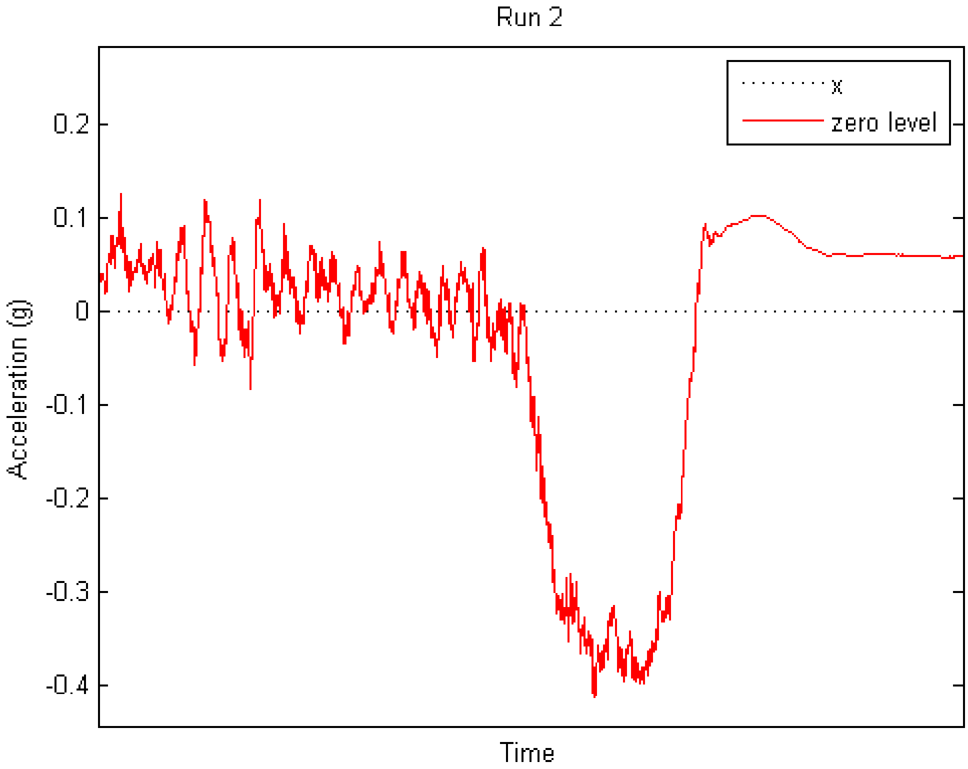
Part III

Appendix

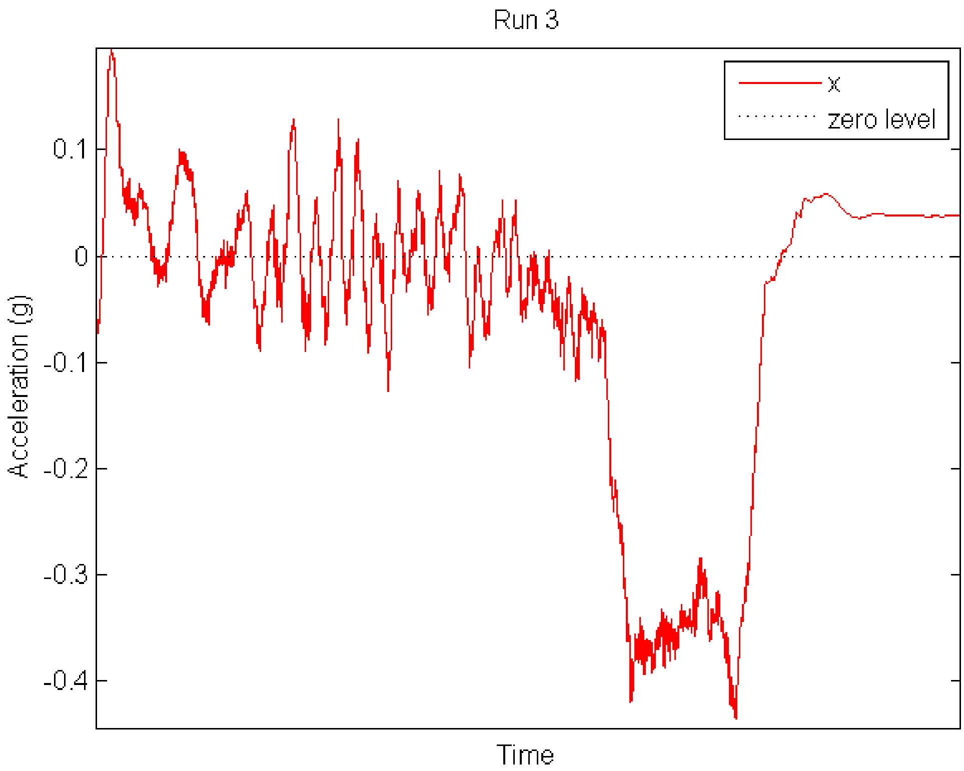
Appendix 1: Acceleration data



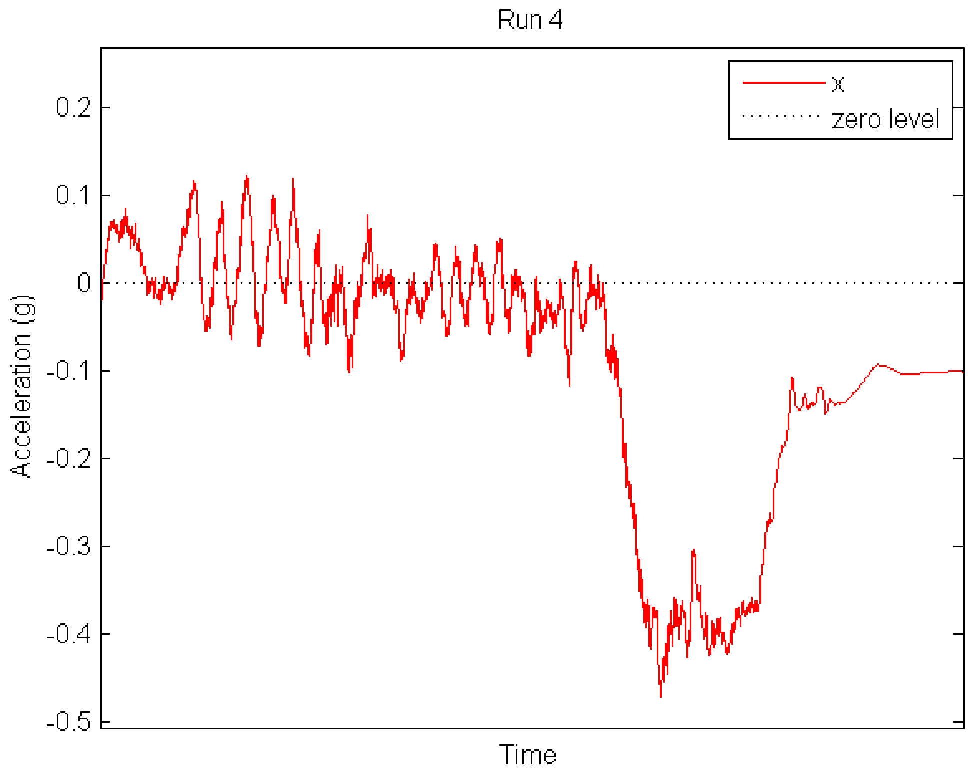
Run nro			1
Bicycle			Hybrid
Time			morning
Road surface conditions			Hard compacted ice
Tire pressure, rear	p	[bar]	2,9
Tire pressure, front	p	[bar]	3,4
Tire shore hardness, rear			61,4
Tire shore hardness, front			60,0
Mass, total	m	[kg]	89,0
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Initial speed	υ	[km/h]	27
Initial speed	υ	[m/s]	7,50
Braking distance	l	[m]	8,3
Friction, braking distance	μb		0,35
Friction, accelerometer	μa		0,35
Absolute error	|Δμa-μb|		0,00



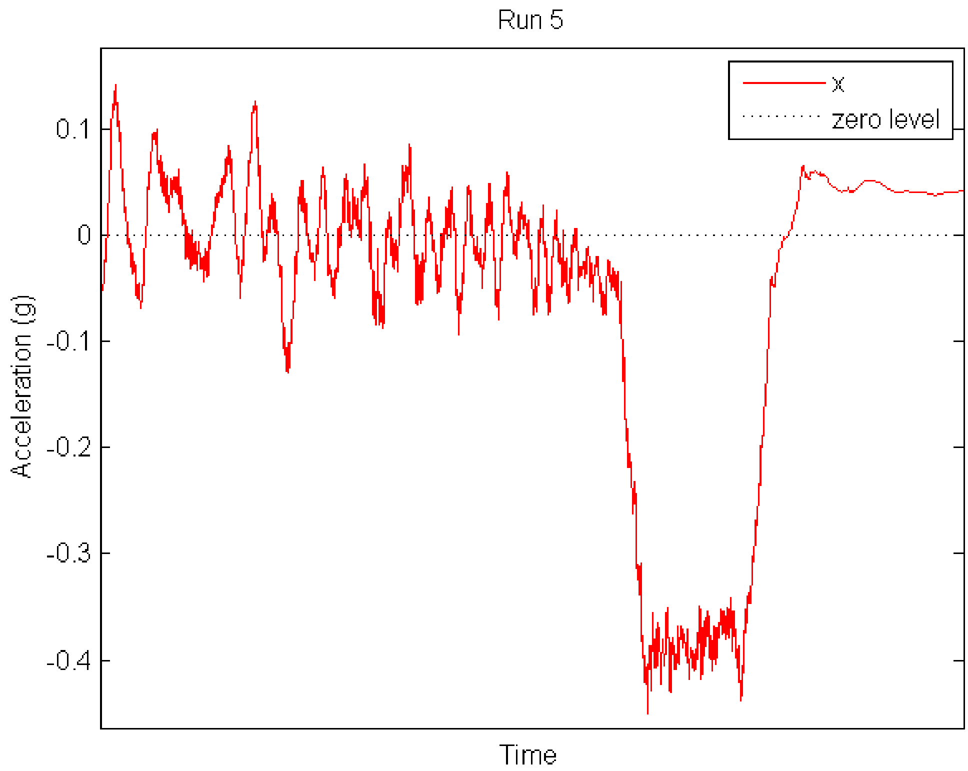
Run nro			2
Bicycle			Hybrid
Time			morning
Road surface conditions			Hard compacted ice
Tire pressure, rear	p	[bar]	2,9
Tire pressure, front	p	[bar]	3,4
Tire shore hardness, rear			61,4
Tire shore hardness, front			60,0
Mass, total	m	[kg]	89,0
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Initial speed	υ	[km/h]	25,5
Initial speed	υ	[m/s]	7,08
Braking distance	l	[m]	8,8
Friction, braking distance	μb		0,29
Friction, accelerometer	μa		0,31
Absolute error	|Δμa-μb|		0,02



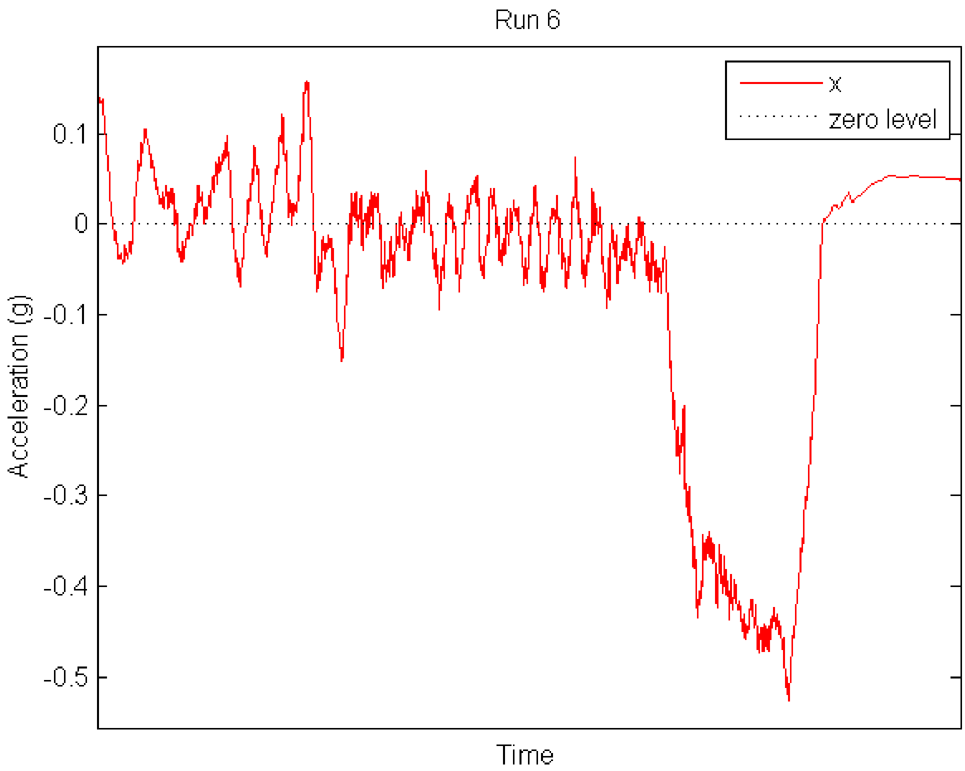
Run nro			3
Bicycle			Hybrid
Time			morning
Road surface conditions			Hard compacted ice
Tire pressure, rear	p	[bar]	2,9
Tire pressure, front	p	[bar]	3,4
Tire shore hardness, rear			61,4
Tire shore hardness, front			60,0
Mass, total	m	[kg]	89,0
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Initial speed	υ	[km/h]	25,5
Initial speed	υ	[m/s]	7,08
Braking distance	ꞁ	[m]	8,0
Friction, braking distance	μb		0,32
Friction, accelerometer	μa		0,32
Absolute error	|Δμa-μb|		0,00



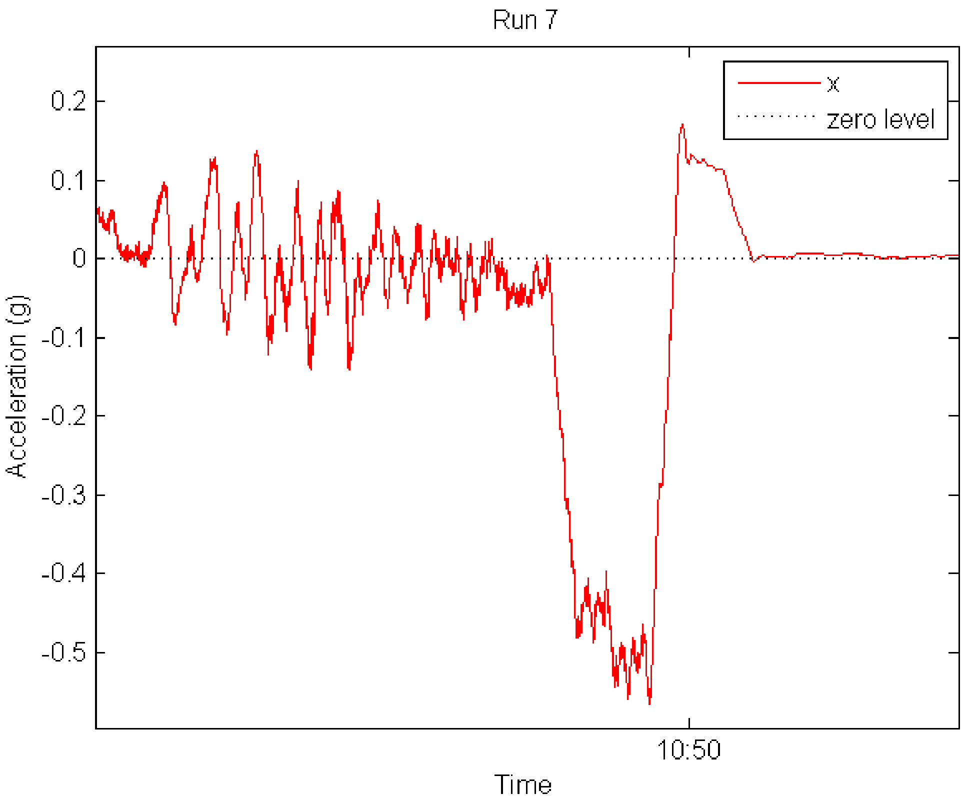
Run nro			4
Bicycle			Hybrid
Time			morning
Road surface conditions			Hard compacted ice
Tire pressure, rear	p	[bar]	2,9
Tire pressure, front	p	[bar]	3,4
Tire shore hardness, rear			61,4
Tire shore hardness, front			60,0
Mass, total	m	[kg]	89,0
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Initial speed	υ	[km/h]	26
Initial speed	υ	[m/s]	7,22
Braking distance	l	[m]	7,4
Friction, braking distance	μb		0,36
Friction, accelerometer	μa		0,34
Absolute error	|Δμa-μb|		0,02



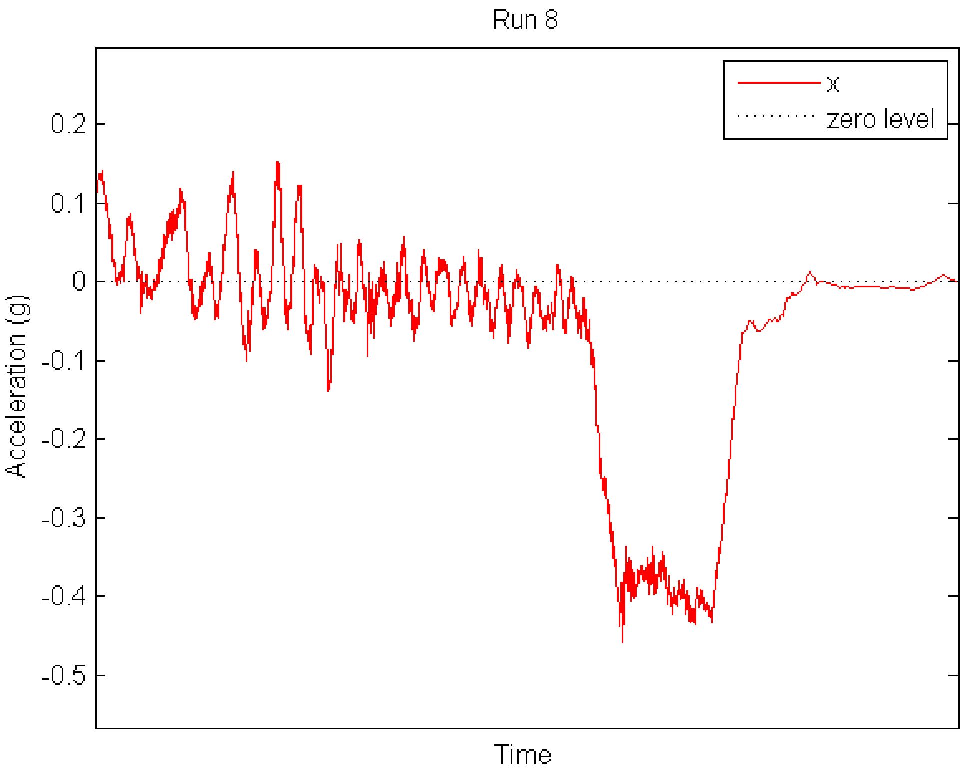
Run nro			5
Bicycle			Hybrid
Time			morning
Road surface conditions			Hard compacted ice
Tire pressure, rear	p	[bar]	2,9
Tire pressure, front	p	[bar]	3,4
Tire shore hardness, rear			61,4
Tire shore hardness, front			60,0
Mass, total	m	[kg]	89,0
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Initial speed	υ	[km/h]	26
Initial speed	υ	[m/s]	7,22
Braking distance	l	[m]	7,9
Friction, braking distance	μb		0,34
Friction, accelerometer	μa		0,34
Absolute error	|Δμa-μb|		0,00



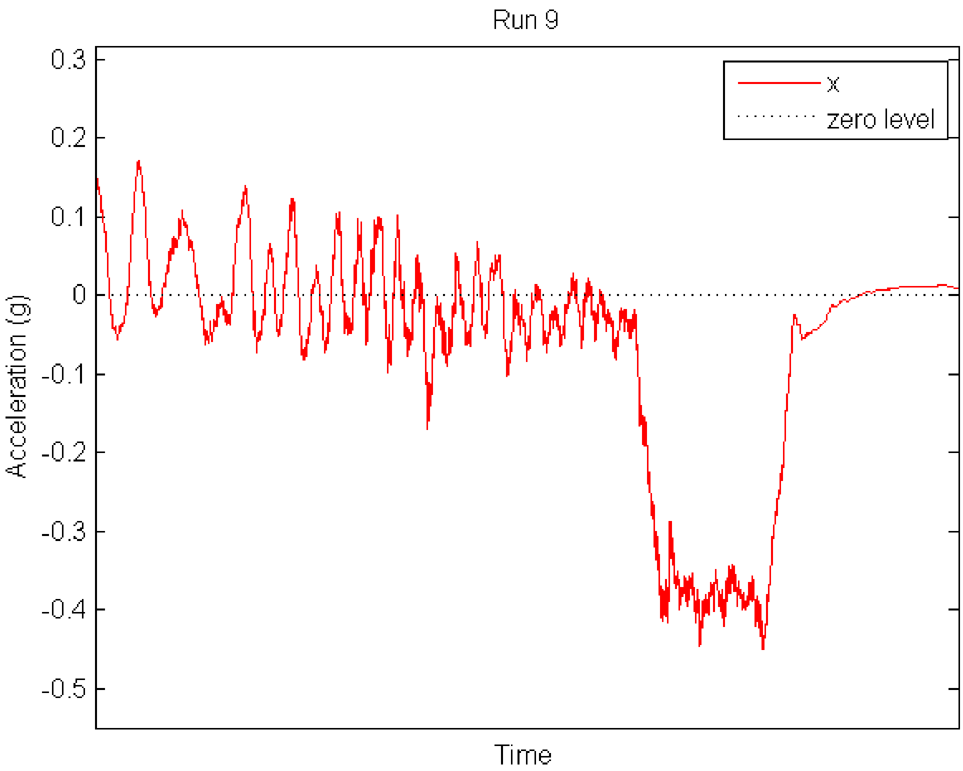
Run nro			6
Bicycle			Hybrid
Time			morning
Road surface conditions			Hard compacted ice
Tire pressure, rear	p	[bar]	2,9
Tire pressure, front	p	[bar]	3,4
Tire shore hardness, rear			61,4
Tire shore hardness, front			60,0
Mass, total	m	[kg]	89,0
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Initial speed	υ	[km/h]	26
Initial speed	υ	[m/s]	7,22
Braking distance	ɭ	[m]	7,6
Friction, braking distance	μb		0,35
Friction, accelerometer	μa		0,36
Absolute error	|Δμa-μb|		0,01



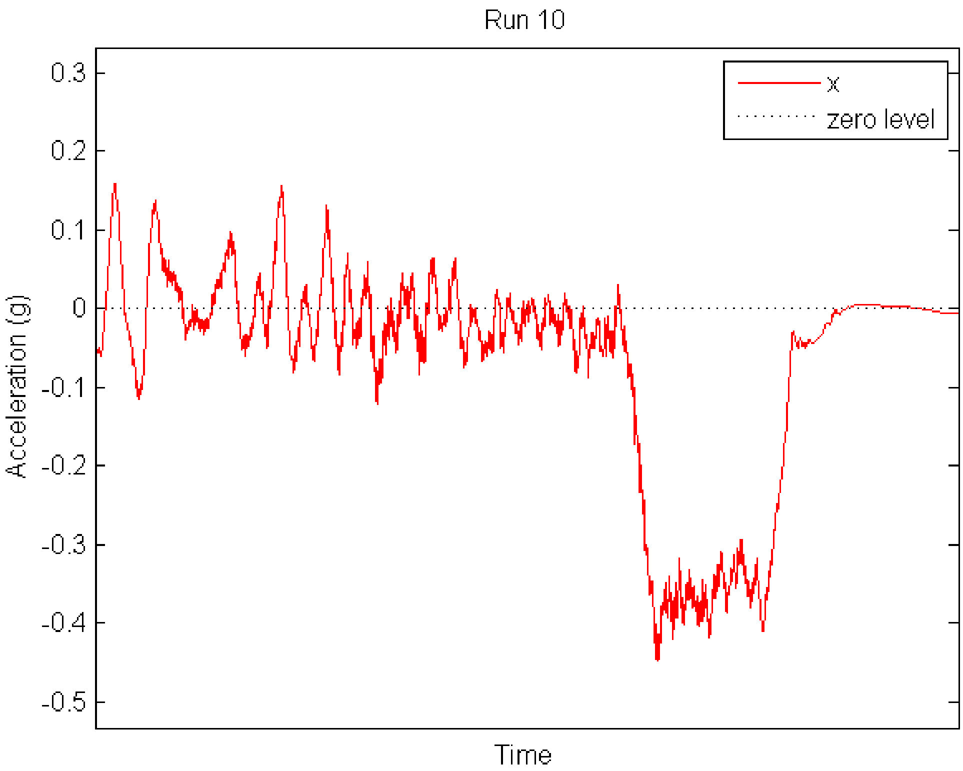
Run nro			8
Bicycle			Hybrid
Time			morning
Road surface conditions			Hard compacted ice
Tire pressure, rear	p	[bar]	2,9
Tire pressure, front	p	[bar]	3,4
Tire shore hardness, rear			61,4
Tire shore hardness, front			60,0
Mass, total	m	[kg]	89,0
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Initial speed	υ	[km/h]	27
Initial speed	υ	[m/s]	7,50
Braking distance	ɭ	[m]	7,4
Friction, braking distance	μb		0,39
Friction, accelerometer	μa		0,41
Absolute error	|Δμa-μb|		0,02



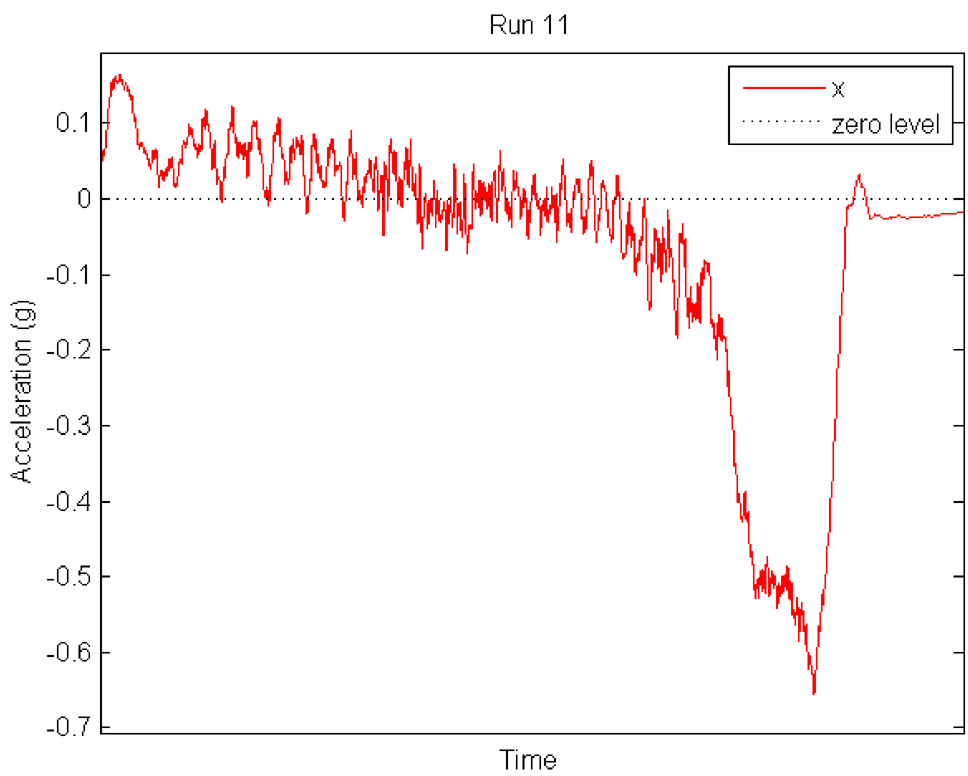
Run nro			8
Bicycle			Hybrid
Time			morning
Road surface conditions			Hard compacted ice
Tire pressure, rear	p	[bar]	2,9
Tire pressure, front	p	[bar]	3,4
Tire shore hardness, rear			61,4
Tire shore hardness, front			60,0
Mass, total	m	[kg]	89,0
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Initial speed	υ	[km/h]	25,5
Initial speed	υ	[m/s]	7,08
Braking distance	ꞁ	[m]	7,0
Friction, braking distance	μb		0,37
Friction, accelerometer	μa		0,34
Absolute error	|Δμa-μb|		0,03



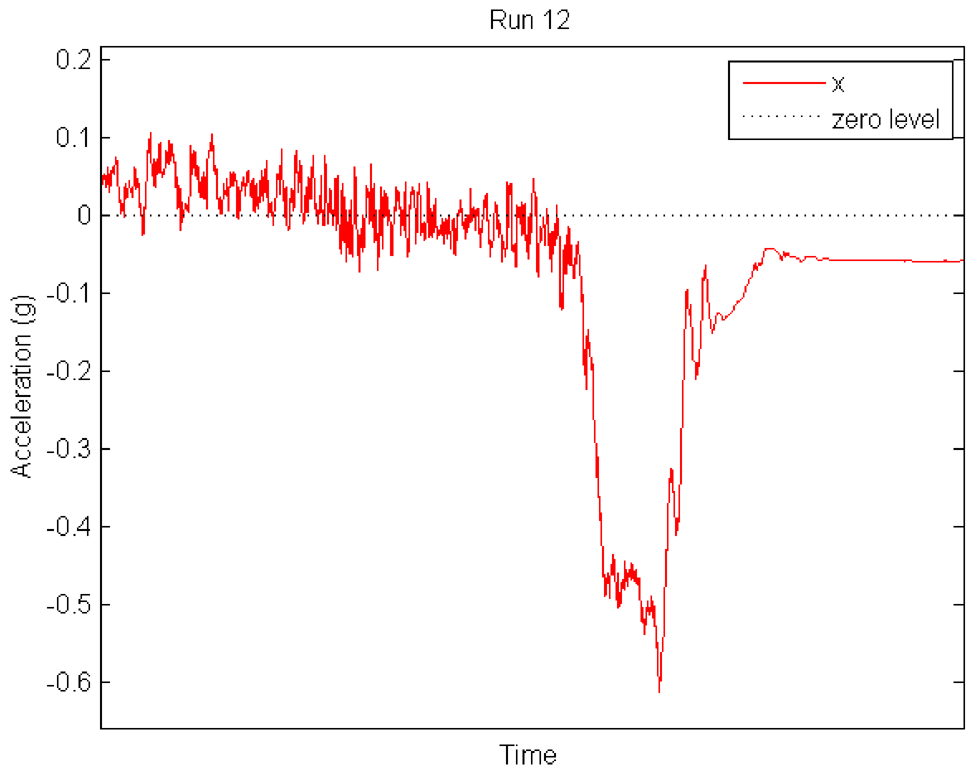
Run nro			9
Bicycle			Hybrid
Time			morning
Road surface conditions			Hard compacted ice
Tire pressure, rear	p	[bar]	2,9
Tire pressure, front	p	[bar]	3,4
Tire shore hardness, rear			61,4
Tire shore hardness, front			60,0
Mass, total	m	[kg]	89,0
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Initial speed	υ	[km/h]	26
Initial speed	υ	[m/s]	7,22
Braking distance	ɭ	[m]	7,9
Friction, braking distance	μb		0,34
Friction, accelerometer	μa		0,34
Absolute error	|Δμa-μb|		0,00



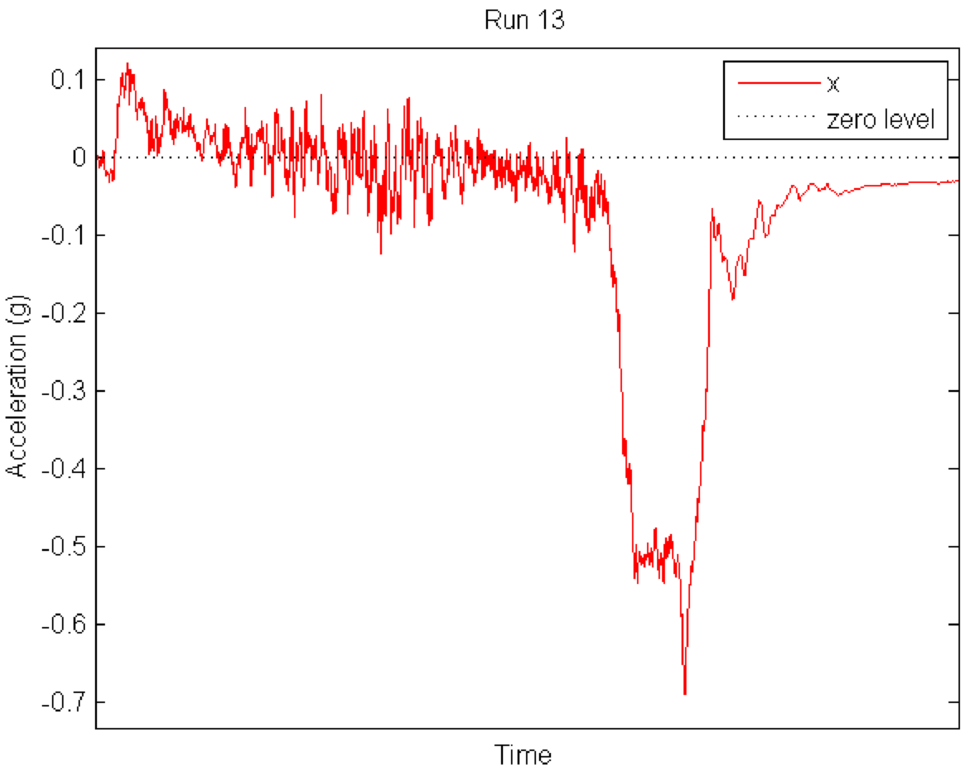
Run nro			10
Bicycle			Hybrid
Time			morning
Road surface conditions			Hard compacted ice
Tire pressure, rear	p	[bar]	2,9
Tire pressure, front	p	[bar]	3,4
Tire shore hardness, rear			61,4
Tire shore hardness, front			60,0
Mass, total	m	[kg]	89,0
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Initial speed	υ	[km/h]	26
Initial speed	υ	[m/s]	7,22
Braking distance	ɭ	[m]	7,9
Friction, braking distance	μb		0,34
Friction, accelerometer	μa		0,32
Absolute error	|Δμa-μb|		0,02



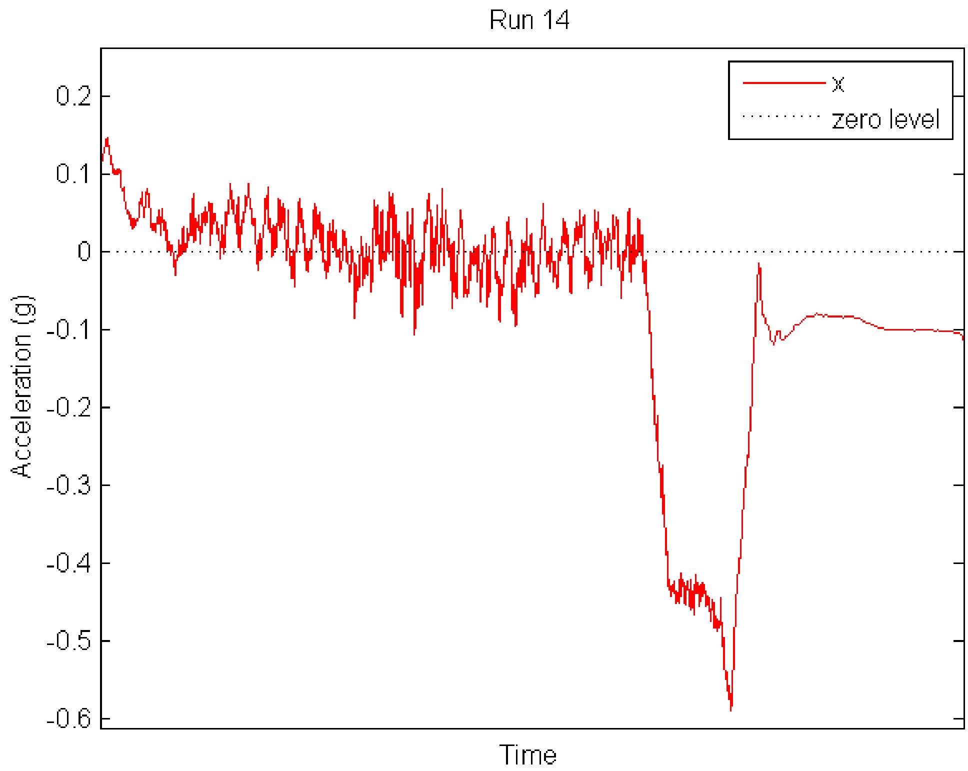
Run nro			11
Bicycle			Off-road
Time			Morning
Road surface conditions			Hard compacted ice
Tire pressure, rear	p	[bar]	2,0
Tire pressure, front	p	[bar]	2,0
Tire shore hardness, rear			54,0
Tire shore hardness, front			60,0
Mass, total	m	[kg]	83,3
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Initial speed	υ	[km/h]	25
Initial speed	υ	[m/s]	6,94
Braking distance	ɭ	[m]	5,8
Friction, braking distance	µb		0,42
Friction, accelerometer	µa		0,46
Absolute error	|Δµa-µb|		0,04



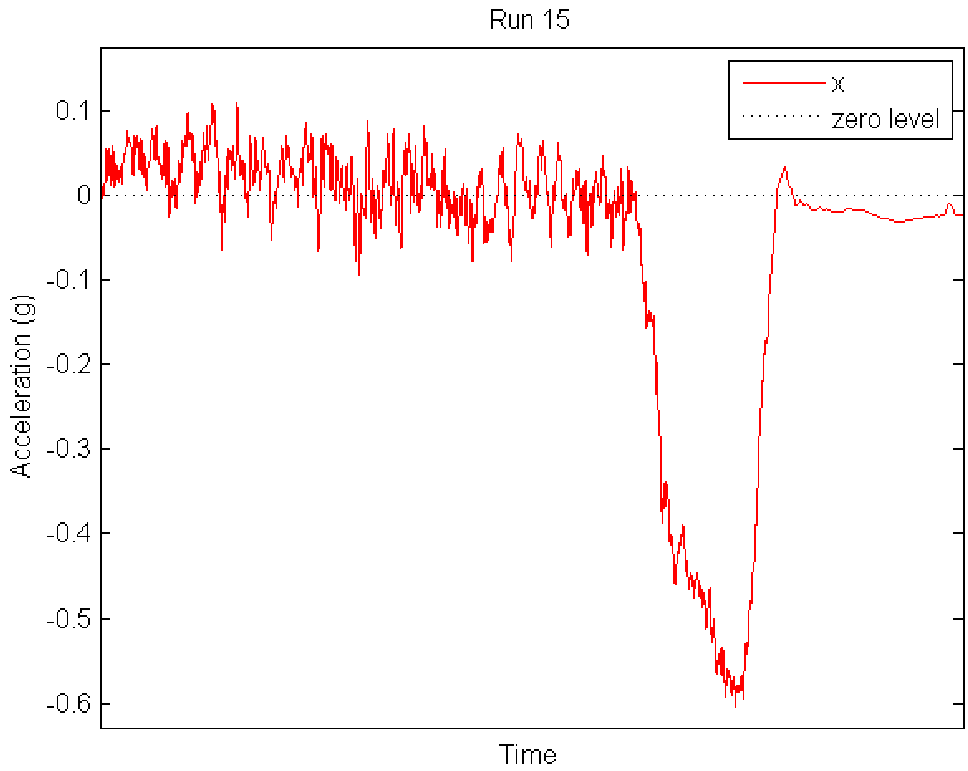
Run nro			12
Bicycle			Off-road
Time			Morning
Road surface conditions			Hard compacted ice
Tire pressure, rear	p	[bar]	2,0
Tire pressure, front	p	[bar]	2,0
Tire shore hardness, rear			54,0
Tire shore hardness, front			60,0
Mass, total	m	[kg]	83,3
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Initial speed	υ	[km/h]	24
Initial speed	υ	[m/s]	6,67
Braking distance	ɭ	[m]	5,2
Friction, braking distance	μb		0,44
Friction, accelerometer	μa		0,43
Absolute error	|Δμa-μb|		0,00



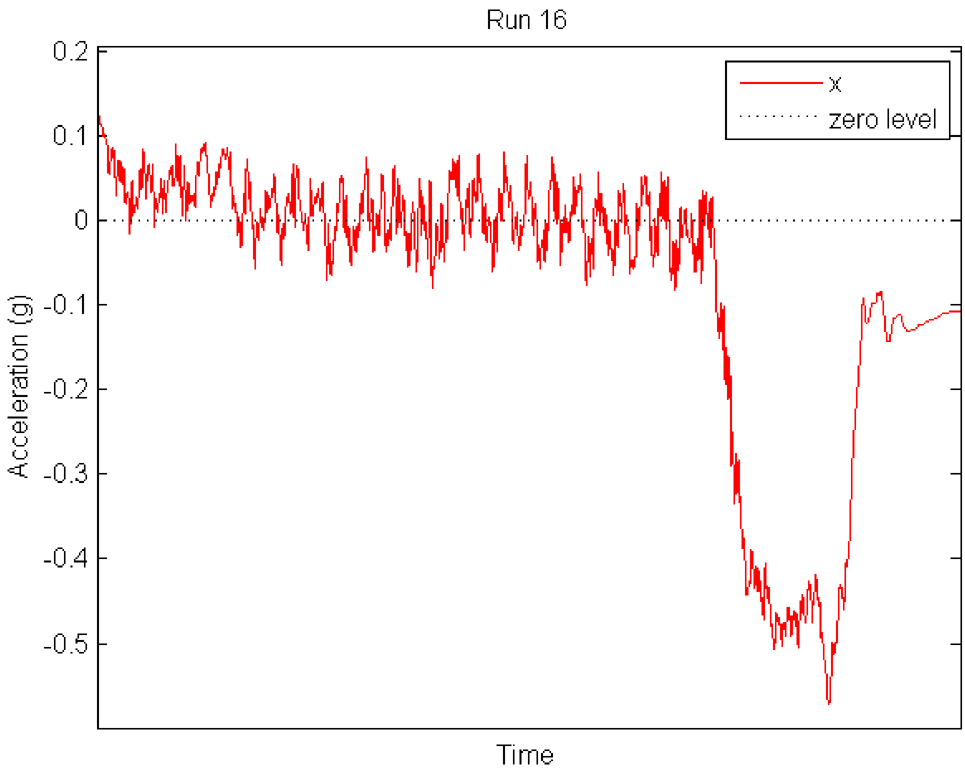
Run nro			13
Bicycle			Off-road
Time			Morning
Road surface conditions			Hard compacted ice
Tire pressure, rear	p	[bar]	2,0
Tire pressure, front	p	[bar]	2,0
Tire shore hardness, rear			54,0
Tire shore hardness, front			60,0
Mass, total	m	[kg]	83,3
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Initial speed	υ	[km/h]	25
Initial speed	υ	[m/s]	6,94
Braking distance	ļ	[m]	5,7
Friction, braking distance	μb		0,43
Friction, accelerometer	μa		0,43
Absolute error	|Δμa-μb|		0,00



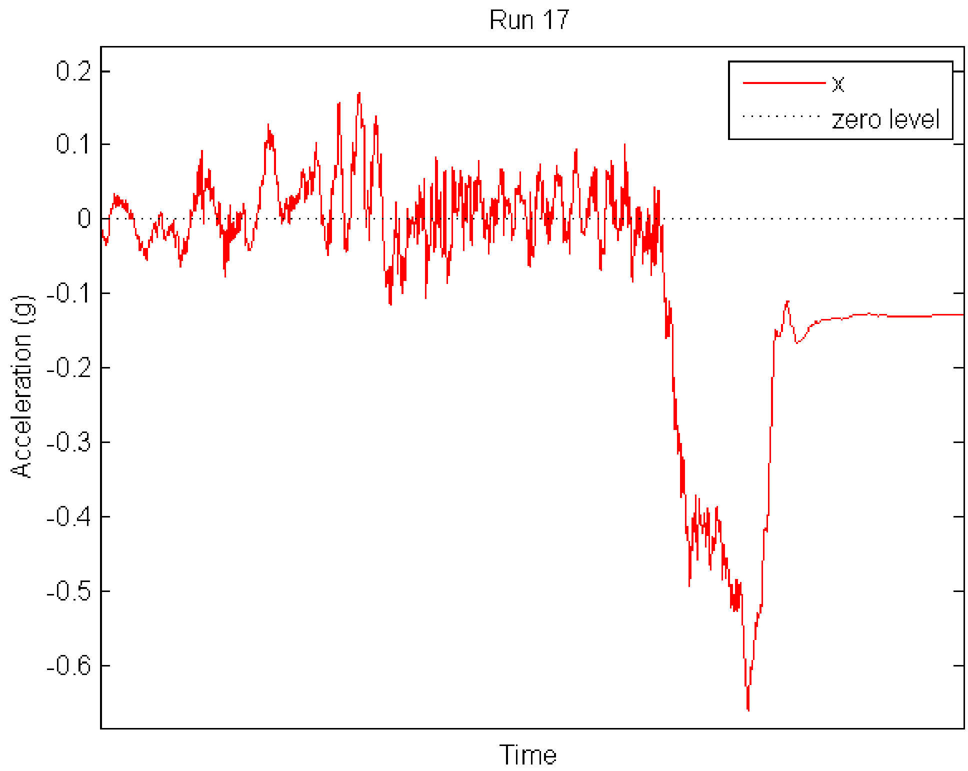
Run nro			14
Bicycle			Off-road
Time			Morning
Road surface conditions			Hard compacted ice
Tire pressure, rear	p	[bar]	2,0
Tire pressure, front	p	[bar]	2,0
Tire shore hardness, rear			54,0
Tire shore hardness, front			60,0
Mass, total	m	[kg]	83,3
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Initial speed	υ	[km/h]	24
Initial speed	υ	[m/s]	6,67
Braking distance	ɭ	[m]	5,4
Friction, braking distance	μb		0,42
Friction, accelerometer	μa		0,39
Absolute error	|Δμa-μb|		0,02



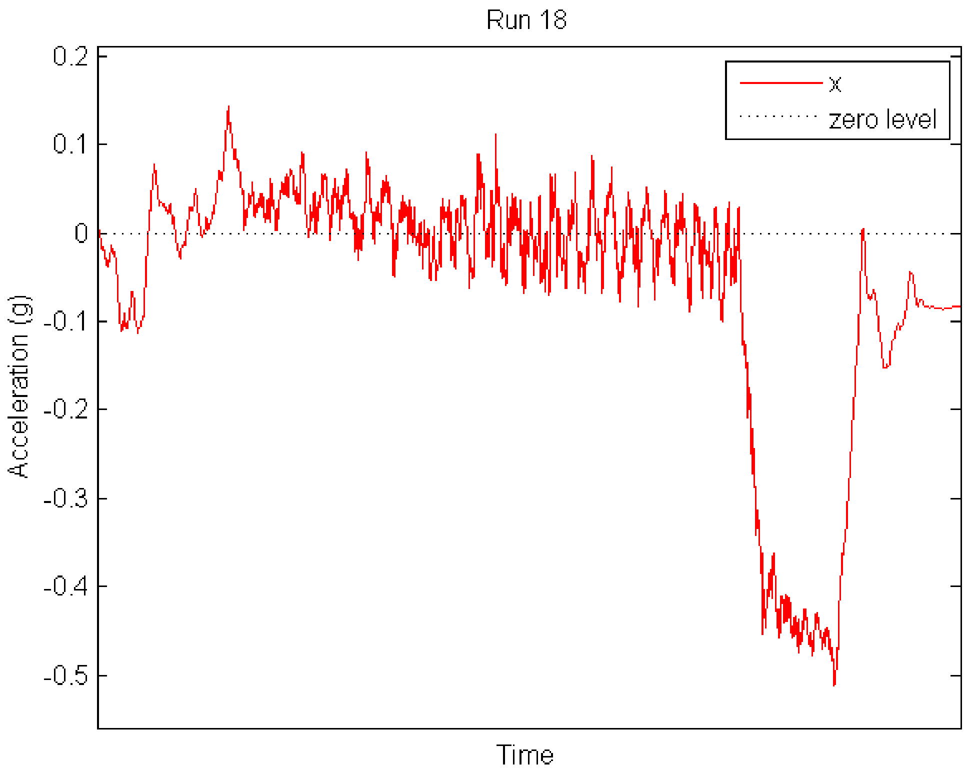
Run nro			15
Bicycle			Off-road
Time			Morning
Road surface conditions			Hard compacted ice
Tire pressure, rear	p	[bar]	2,0
Tire pressure, front	p	[bar]	2,0
Tire shore hardness, rear			54,0
Tire shore hardness, front			60,0
Mass, total	m	[kg]	83,3
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Initial speed	υ	[km/h]	25
Initial speed	υ	[m/s]	6,94
Braking distance	ɭ	[m]	6,1
Friction, braking distance	µb		0,40
Friction, accelerometer	µa		0,40
Absolute error	|Δµa-µb|		0,00



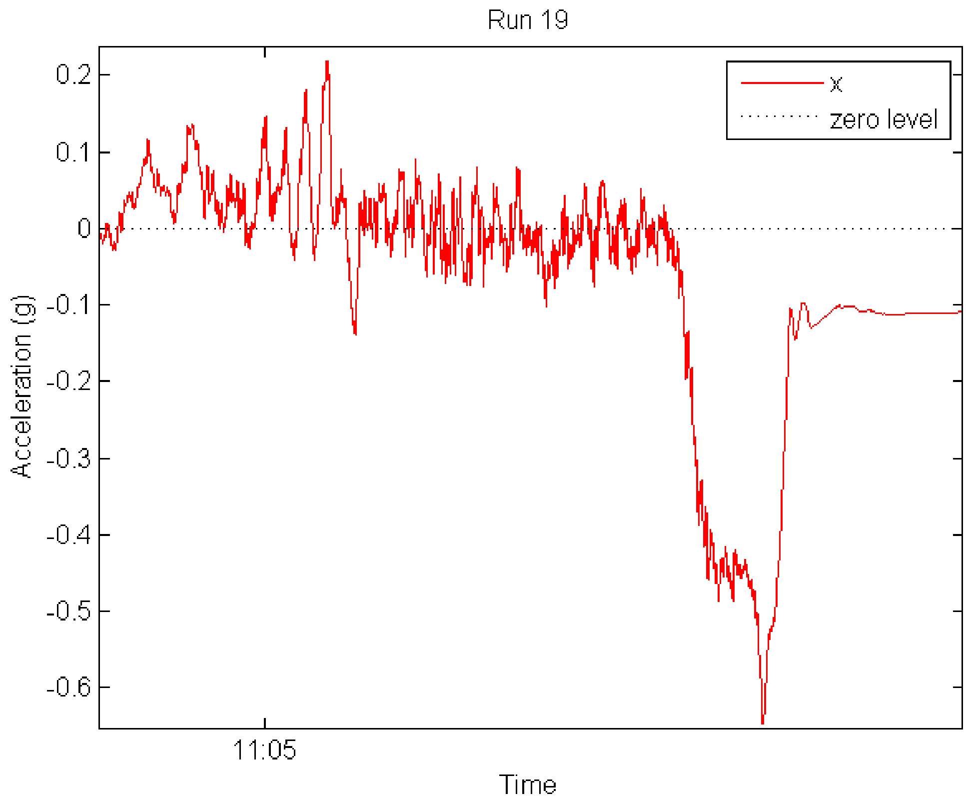
Run nro			16
Bicycle			Off-road
Time			Morning
Road surface conditions			Hard compacted ice
Tire pressure, rear	p	[bar]	2,0
Tire pressure, front	p	[bar]	2,0
Tire shore hardness, rear			54,0
Tire shore hardness, front			60,0
Mass, total	m	[kg]	83,3
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Initial speed	υ	[km/h]	25
Initial speed	υ	[m/s]	6,94
Braking distance	ɭ	[m]	6,3
Friction, braking distance	μb		0,39
Friction, accelerometer	μa		0,42
Absolute error	|Δμa-μb|		0,03



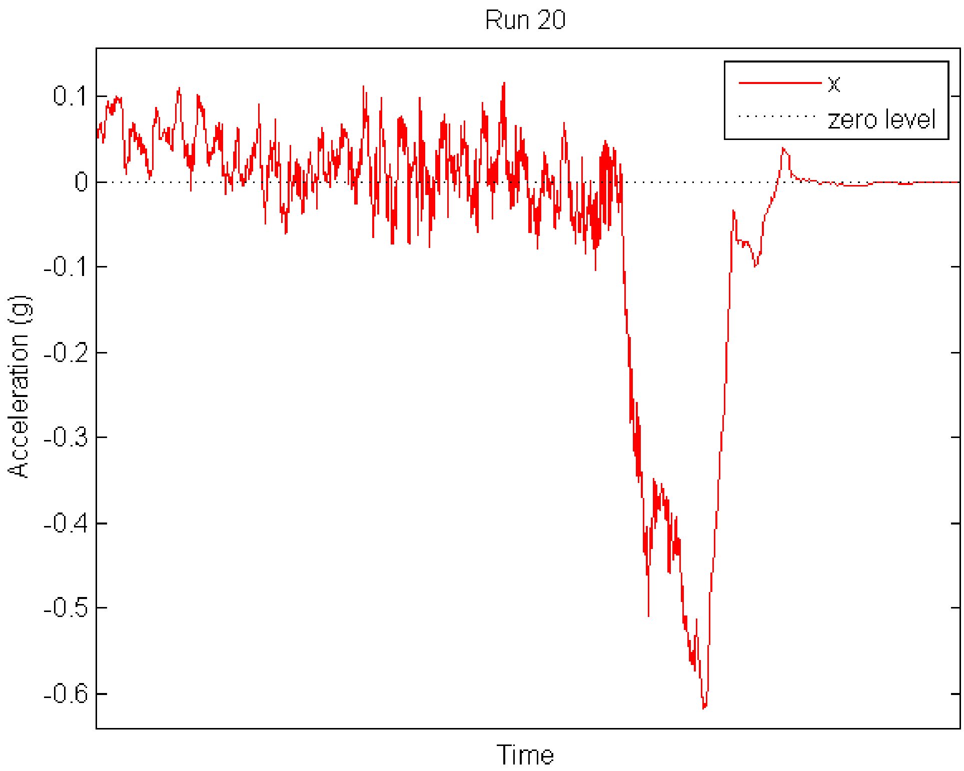
Run nro			17
Bicycle			Off-road
Time			Morning
Road surface conditions			Hard compacted ice
Tire pressure, rear	p	[bar]	2,0
Tire pressure, front	p	[bar]	2,0
Tire shore hardness, rear			54,0
Tire shore hardness, front			60,0
Mass, total	m	[kg]	83,3
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Initial speed	υ	[km/h]	25
Initial speed	υ	[m/s]	6,94
Braking distance	ɭ	[m]	6,1
Friction, braking distance	μb		0,40
Friction, accelerometer	μa		0,43
Absolute error	|Δμa-μb|		0,03



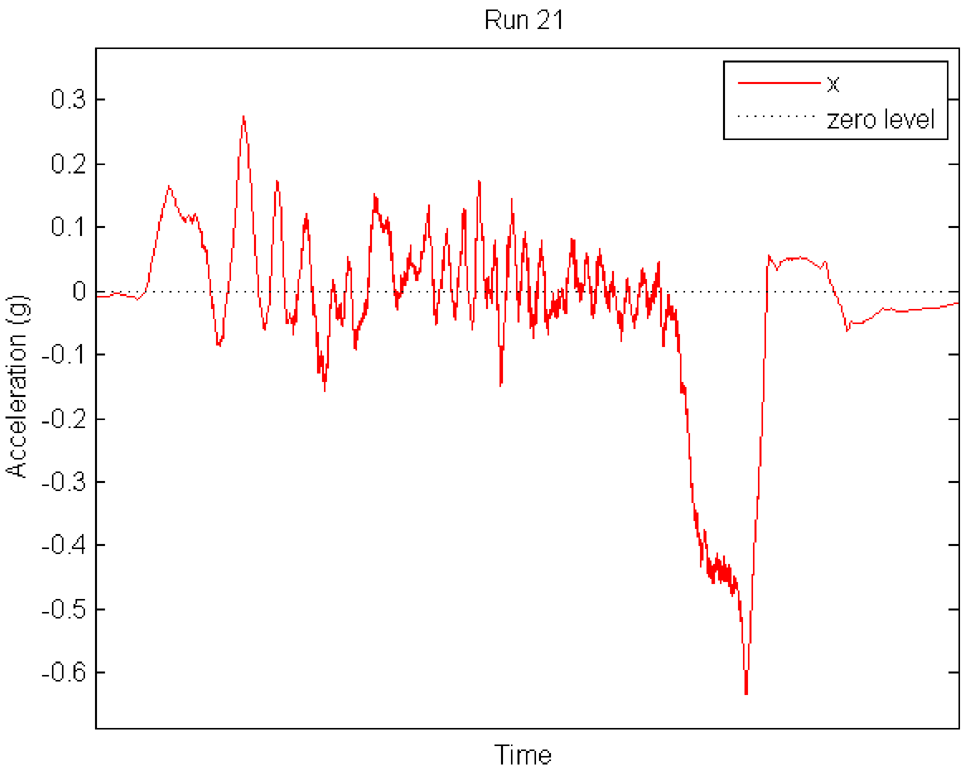
Run nro			18
Bicycle			Off-road
Time			Morning
Road surface conditions			Hard compacted ice
Tire pressure, rear	p	[bar]	2,0
Tire pressure, front	p	[bar]	2,0
Tire shore hardness, rear			54,0
Tire shore hardness, front			60,0
Mass, total	m	[kg]	83,3
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Initial speed	υ	[km/h]	25
Initial speed	υ	[m/s]	6,94
Braking distance	l	[m]	6,0
Friction, braking distance	μb		0,41
Friction, accelerometer	μa		0,36
Absolute error	|Δμa-μb|		0,05



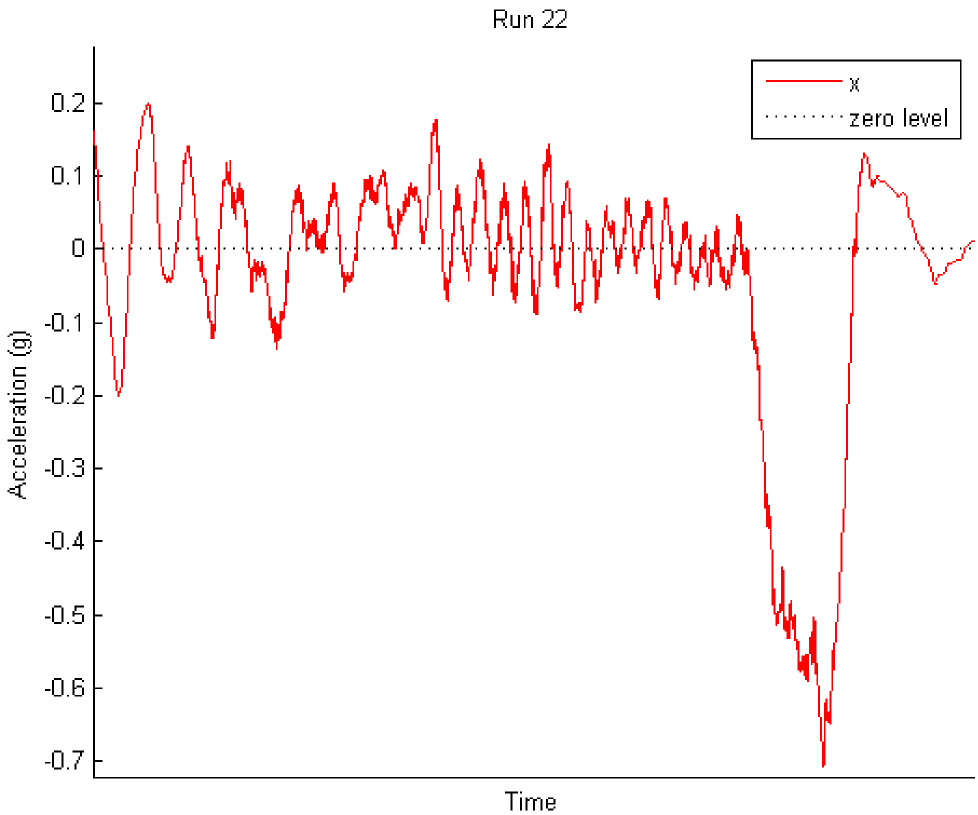
Run nro			19
Bicycle			Off-road
Time			Morning
Road surface conditions			Hard compacted ice
Tire pressure, rear	p	[bar]	2,0
Tire pressure, front	p	[bar]	2,0
Tire shore hardness, rear			54,0
Tire shore hardness, front			60,0
Mass, total	m	[kg]	83,3
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Initial speed	υ	[km/h]	23
Initial speed	υ	[m/s]	6,39
Braking distance	ɭ	[m]	6,7
Friction, braking distance	μb		0,31
Friction, accelerometer	μa		0,42
Absolute error	|Δμa-μb|		0,11



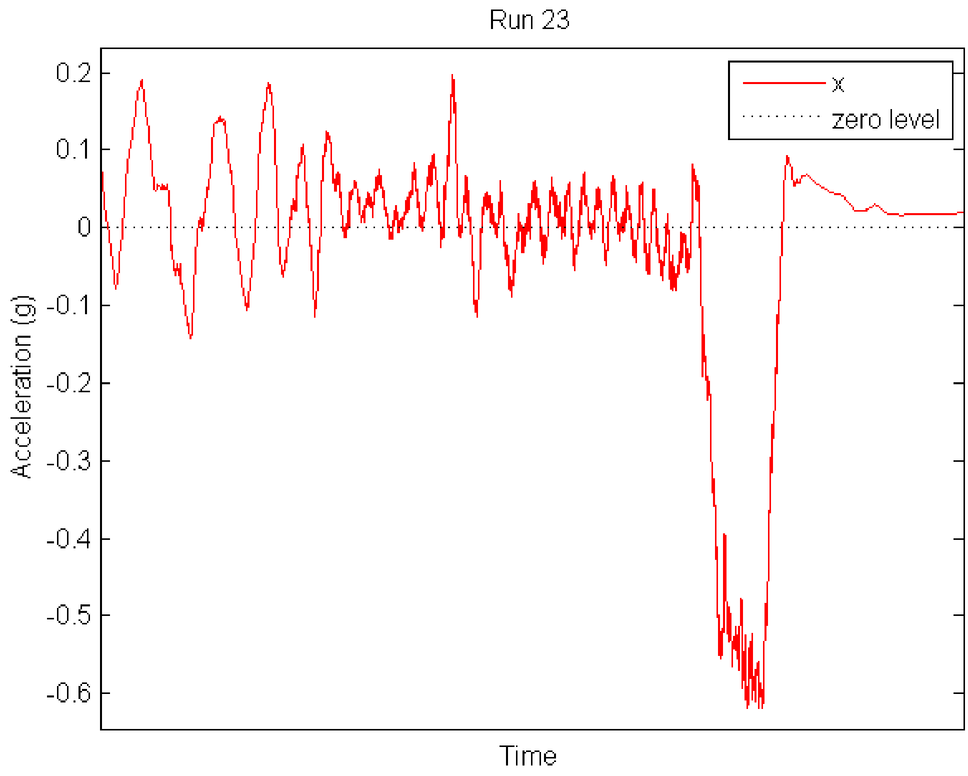
Run nro			20
Bicycle			Off-road
Time			Morning
Road surface conditions			Hard compacted ice
Tire pressure, rear	p	[bar]	2,0
Tire pressure, front	p	[bar]	2,0
Tire shore hardness, rear			54,0
Tire shore hardness, front			60,0
Mass, total	m	[kg]	83,3
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Initial speed	υ	[km/h]	24
Initial speed	υ	[m/s]	6,67
Braking distance	ɭ	[m]	5,9
Friction, braking distance	μb		0,38
Friction, accelerometer	μa		0,37
Absolute error	|Δμa-μb|		0,01



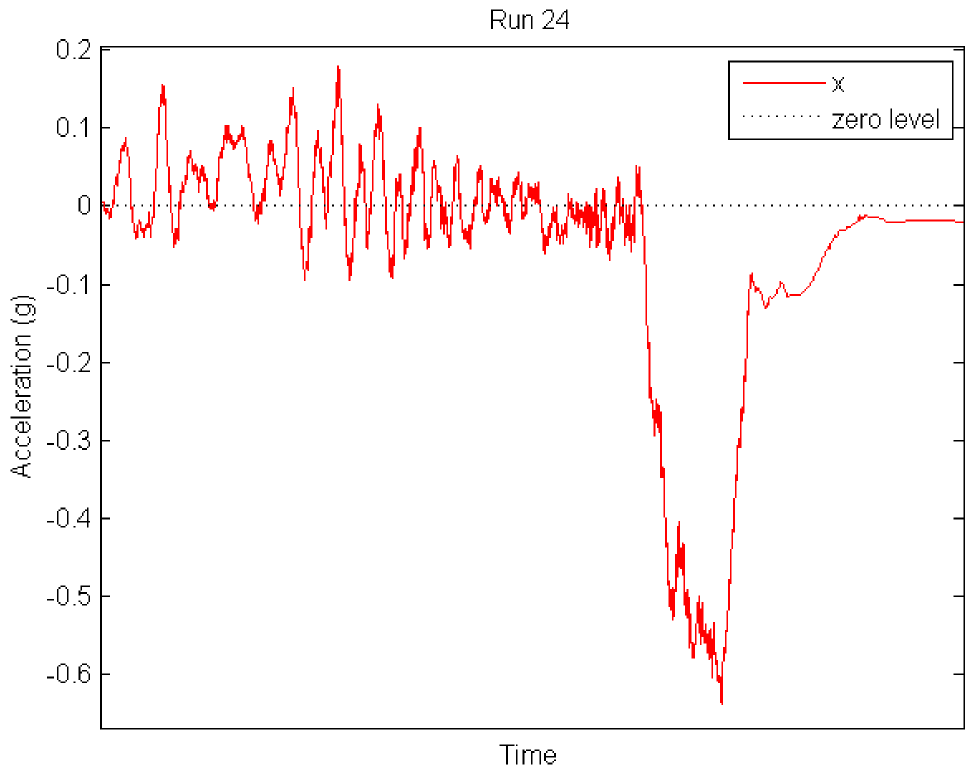
Run nro			21
Bicycle			Hybrid
Time			Afternoon
Road surface conditions			Large grained compacted ice
Tire pressure, rear	p	[bar]	2,9
Tire pressure, front	p	[bar]	3,4
Tire shore hardness, rear			61,4
Tire shore hardness, front			60,0
Mass, total	m	[kg]	89,0
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Braking distance	l	[m]	5,1
Friction, accelerometer	µa		0,36



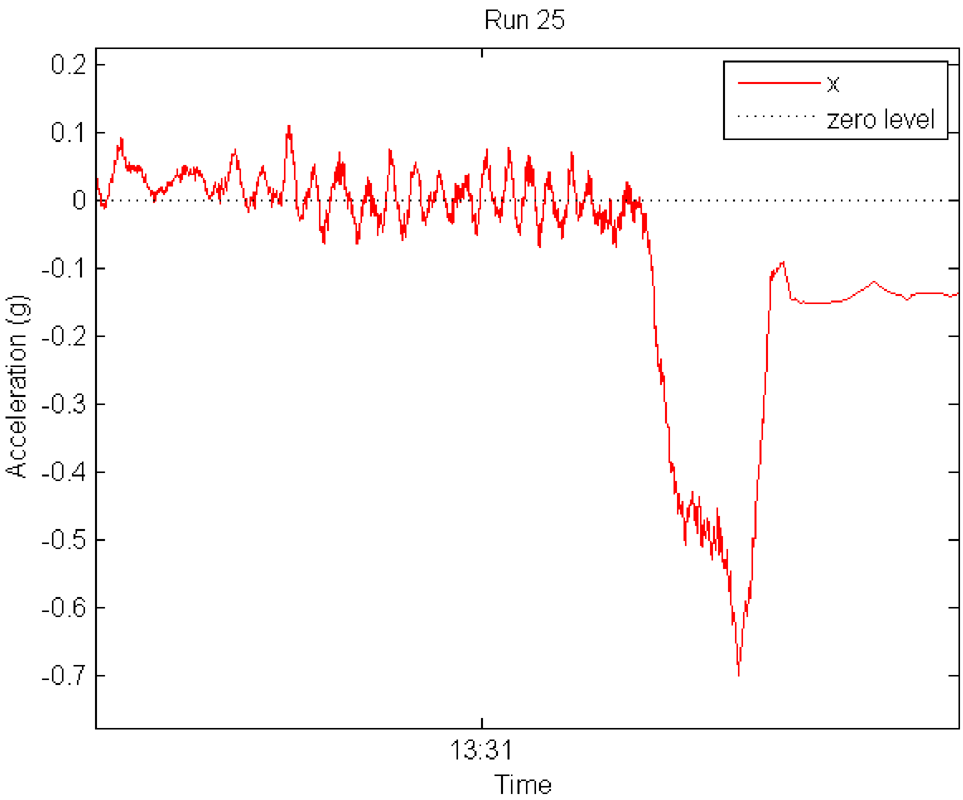
Run nro			22
Bicycle			Hybrid
Time			Afternoon
Road surface conditions			Large grained compacted ice
Tire pressure, rear	p	[bar]	2,9
Tire pressure, front	p	[bar]	3,4
Tire shore hardness, rear			61,4
Tire shore hardness, front			60,0
Mass, total	m	[kg]	89,0
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Braking distance	l	[m]	5,2
Friction, accelerometer	μa		0,44



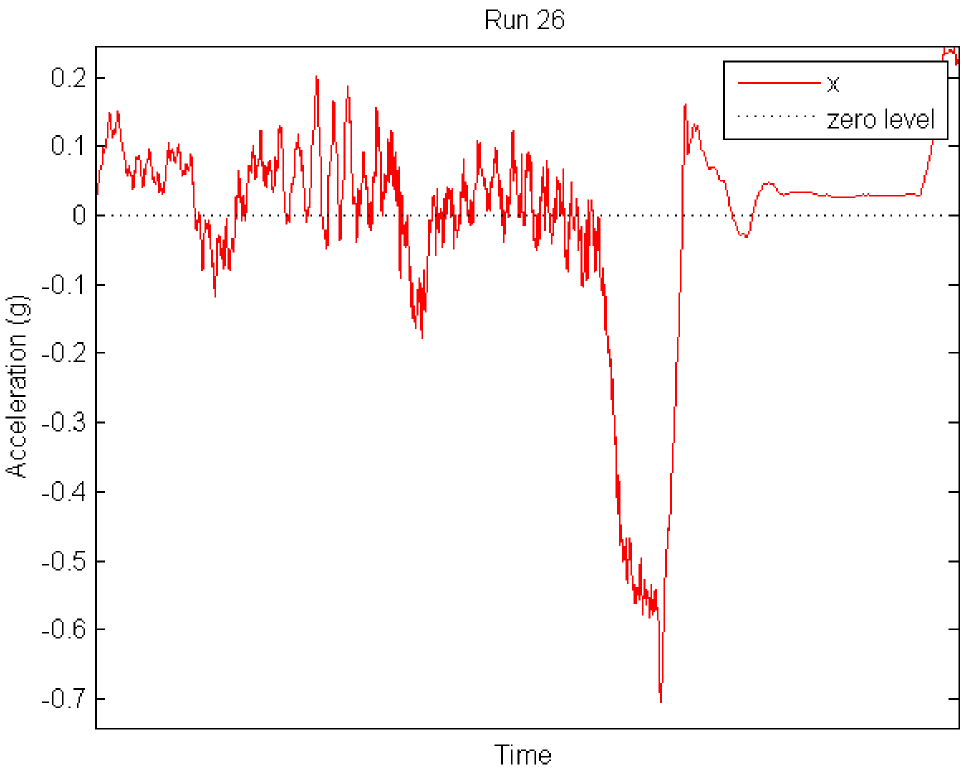
Run nro			23
Bicycle			Hybrid
Time			Afternoon
Road surface conditions			Large grained compacted ice
Tire pressure, rear	p	[bar]	2,9
Tire pressure, front	p	[bar]	3,4
Tire shore hardness, rear			61,4
Tire shore hardness, front			60,0
Mass, total	m	[kg]	89,0
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Braking distance	l	[m]	5,1
Friction, accelerometer	μa		0,39



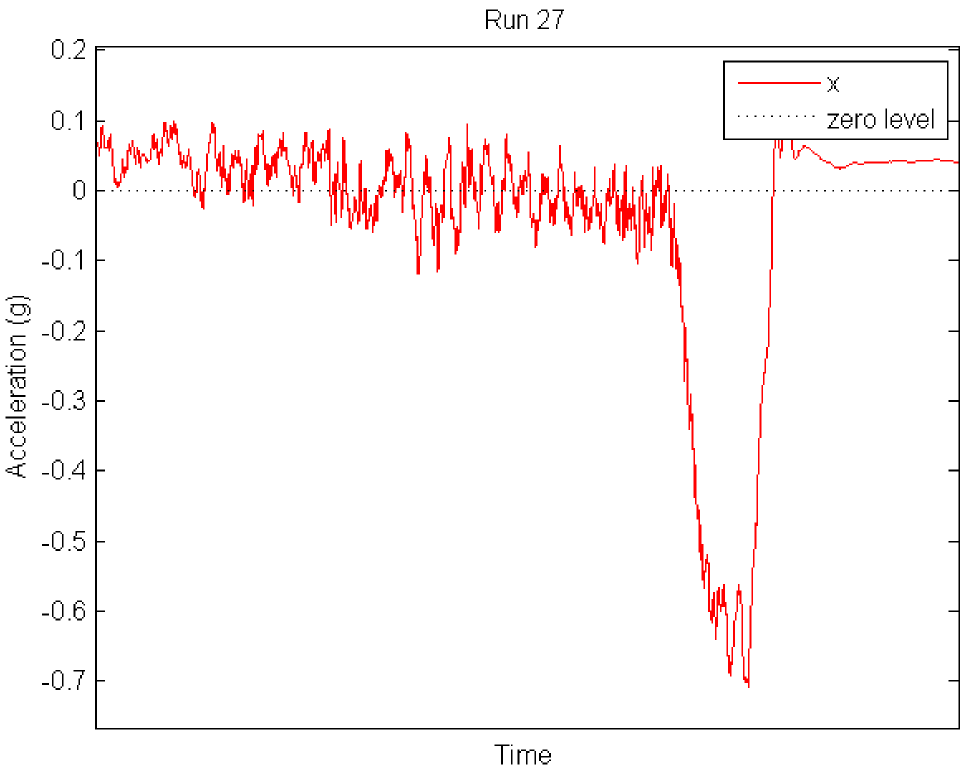
Run nro			24
Bicycle			Hybrid
Time			Afternoon
Road surface conditions			Large grained compacted ice
Tire pressure, rear	p	[bar]	2,9
Tire pressure, front	p	[bar]	3,4
Tire shore hardness, rear			61,4
Tire shore hardness, front			60,0
Mass, total	m	[kg]	89,0
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Braking distance	l	[m]	5,1
Friction, accelerometer	μa		0,44



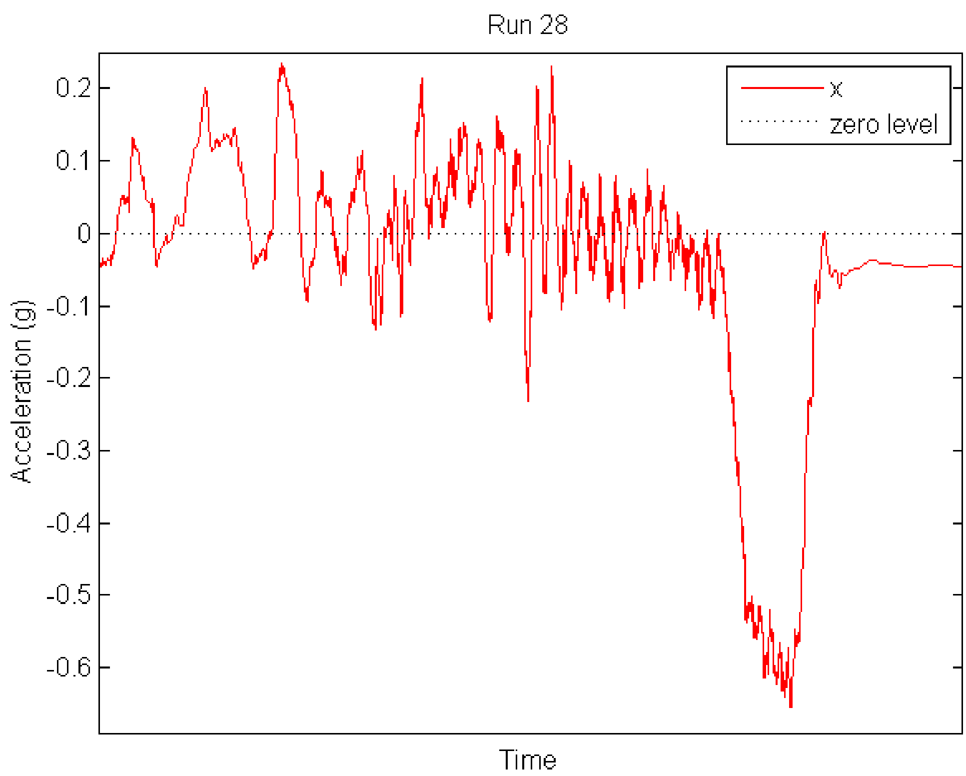
Run nro			25
Bicycle			Hybrid
Time			Afternoon
Road surface conditions			Large grained compacted ice
Tire pressure, rear	p	[bar]	2,9
Tire pressure, front	p	[bar]	3,4
Tire shore hardness, rear			61,4
Tire shore hardness, front			60,0
Mass, total	m	[kg]	89,0
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Braking distance	l	[m]	5,6
Friction, accelerometer	μa		0,45



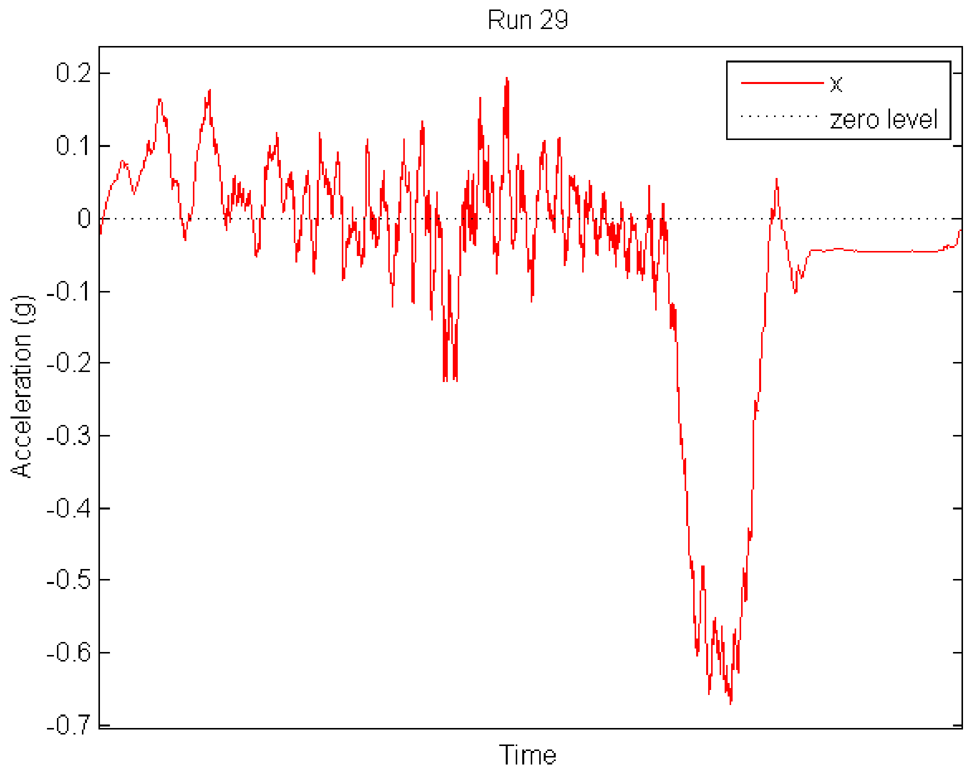
Run nro			26
Bicycle			Off-road
Time			Afternoon
Road surface conditions			Large grained compacted ice
Tire pressure, rear	p	[bar]	2,0
Tire pressure, front	p	[bar]	2,0
Tire shore hardness, rear			54,0
Tire shore hardness, front			60,0
Mass, total	m	[kg]	83,3
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Braking distance	l	[m]	4,2
Friction, accelerometer	µa		0,41



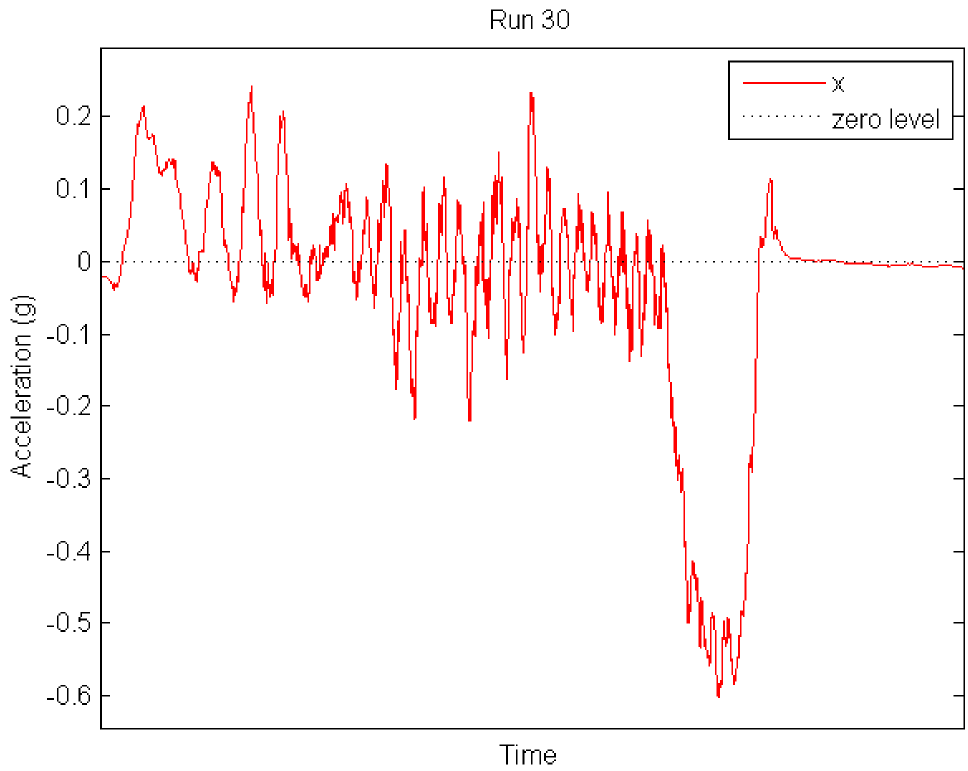
Run nro			27
Bicycle			Off-road
Time			Afternoon
Road surface conditions			Large grained compacted ice
Tire pressure, rear	p	[bar]	2,0
Tire pressure, front	p	[bar]	2,0
Tire shore hardness, rear			54,0
Tire shore hardness, front			60,0
Mass, total	m	[kg]	83,3
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Braking distance	l	[m]	4,6
Friction, accelerometer	µa		0,44



Run nro			28
Bicycle			Off-road
Time			Afternoon
Road surface conditions			Large grained compacted ice
Tire pressure, rear	p	[bar]	2,0
Tire pressure, front	p	[bar]	2,0
Tire shore hardness, rear			54,0
Tire shore hardness, front			60,0
Mass, total	m	[kg]	83,3
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Braking distance	l	[m]	4,3
Friction, accelerometer	μa		0,45



Run nro			29
Bicycle			Off-road
Time			Afternoon
Road surface conditions			Large grained compacted ice
Tire pressure, rear	p	[bar]	2,0
Tire pressure, front	p	[bar]	2,0
Tire shore hardness, rear			54,0
Tire shore hardness, front			60,0
Mass, total	m	[kg]	83,3
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Braking distance	l	[m]	4,0
Friction, accelerometer	μa		0,40



Run nro			30
Bicycle			Off-road
Time			Afternoon
Road surface conditions			Large grained compacted ice
Tire pressure, rear	p	[bar]	2,0
Tire pressure, front	p	[bar]	2,0
Tire shore hardness, rear			54,0
Tire shore hardness, front			60,0
Mass, total	m	[kg]	83,3
Temperature, road	T	[°C]	-9,0
Temperature, air	T	[°C]	-1,4
Braking distance	l	[m]	5,1
Friction, accelerometer	μa		0,41